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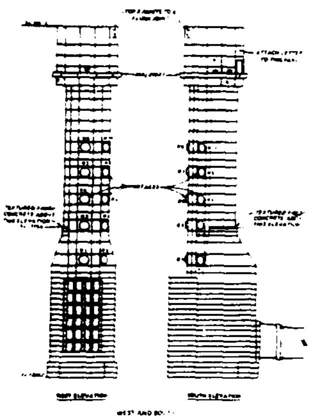

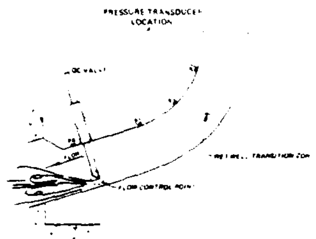

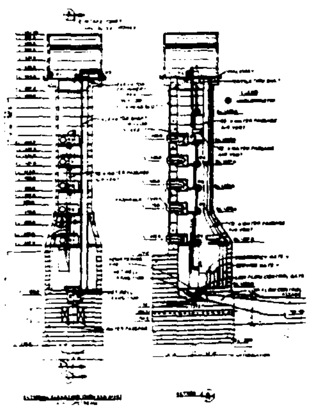

STRUCTURES LABORATORY

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VIBRATION STUDY OF THE BLOOMINGTON INTAKE TOWER

by

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This report presents the results of tests conducted to obtain data pertaining to the hydraulic performance and structural response of the intake tower. These data would then be used to compare with findings of earlier measurements and evaluate correlations between the hydraulics and the structural responses. The test program measured wet well transition zone pressures, upper portal pressures, wet well water-surface levels, and structural vibrations. Data reduction and analysis indicated that large pressure surges occurred in the wet well when closing the quality control (QC) valves from the full open position, a flow control shift occurred as the QC valve was opened from 2.9 to 3.0 ft, and the vibration levels monitored were within the safe limits. The structural responses of the intake tower correspond well with previous vibration tests conducted at similar structures.

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PREFACE

This study was conducted during the period April 1984 through May 1986 by the US Army Engineer Waterways Experiment Station (WES) under the sponsorship of the US Army Engineer District, Baltimore. Technical Monitor was Mr. Harry Debes.

The tests were conducted and the report was prepared at WES by Messrs. V. P. Chiarito, Structures Laboratory (SL), and T. L. Fagerburg, Hydraulics Laboratory (HL), under the supervision of Messrs. Bryant Mather, Chief, SL; J. T. Ballard, Assistant Chief, SL; Dr. J. P. Balsara, Chief, Structural Mechanics Division (SMD), SL; Messrs. F. A. Herrmann, Jr., Chief, HL; M. B. Boyd, Chief, Hydraulic Analysis Division, HL; and E. D. Hart, Chief, Prototype Evaluation Branch, HL. Messrs. Robert Walker, formerly of the SMD, SL, and R. Stephen Wright, SMD, SL, conducted the first data acquisition field study.

Acknowledgment is made to Messrs. James L. Pickens, Pat Shows, and Duane Stevens, Data Acquisition Section, Instrumentation Services Division, WES, for instrumentation support, and Messrs. Donald Douglas and Stafford Cooper, Field Investigations Group, Geotechnical Laboratory, WES, for vibration testing support.

COL Dwayne G. Lee, EN, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
atmosphere (standard)	101.325	kilopascals
cubic feet	0.02831685	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
inches	25.4	millimetres
miles	1.609347	metres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

VIBRATION STUDY OF THE BLOOMINGTON INTAKE TOWER

PART I: INTRODUCTION

Project Description

1. Bloomington Dam is located on the North Branch of the Potomac River approximately 45 miles* from Oakland, MD, on the Maryland-West Virginia state line as shown in Figure 1. The location of the intake tower is shown in Figure 2, the plan view of the Bloomington Project.

2. The Bloomington Intake Tower is part of a recently constructed project and is approximately 300 ft high and of axisymmetric geometry with an oblong-type foundation base. There are two portals at five different elevations that can intake water from the stratified layers in the reservoir for water-quality control.

3. The Bloomington Dam Intake Tower was designed to operate in accordance with previously recognized design criteria. Current criteria dictate higher outflow discharges to achieve prescribed downstream water-quality standards. These higher discharges have resulted in noticeable vibrations of the intake tower. Three sets of measurements have been made by the Baltimore District to observe various quality-control (QC) gate operations to determine those gate settings which cause noticeable vibrations. As a result of these studies, restrictive QC gate settings have been imposed.

Statement of the Problem

4. The Baltimore District noted high vibration levels and movement of the Bloomington Intake Tower during operation. The Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), was notified of the problem on 19 April 1984, and requested to measure these vibration levels.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

5. The Structural Mechanics Division (SMD), SL, with the cooperation of the Instrumentation Service Division, WES, planned and executed the initial vibration monitoring. The Baltimore District had developed a test plan for controlled flows which was reviewed by the Hydraulics Laboratory (HL) at WES. Following the test plan, the SMD monitored the vibrations of the tower during the controlled flows. These data were recorded on 24-26 April 1984. The objective of monitoring the vibration levels of the Bloomington Intake Tower was to record vibration data to determine its dynamic properties (natural frequencies, mode shapes, and damping ratios). A modal analysis was used to determine the dynamic flexural and torsional responses of the intake tower during intake operation.

6. The Baltimore District also requested that the HL, WES, review the hydraulic data collected during their three measurement periods. After review, WES provided a letter report assessing the results of the review and proposing further measurements. The additional measurements were made in conjunction with additional testing conducted by the SL.

7. This second test series was conducted during the period 15-27 April 1985. This series was to acquire additional data that would help determine the source of the vibrations. It was thought that the vibrations might be caused by the hydraulic phenomenon occurring in the wet well transitions or in the upper wet well due to flow characteristics from the intake portals. Additional accelerometers were positioned to determine responses of the tower at elevations not previously measured. Also, correlations would be determined between accelerations (motion) and pressures, if any.

Purpose

8. The principal objectives of the tests conducted in this study were to obtain prototype data on wet well mean pressures, dynamic pressures, and structural vibrations. These data would then be used to compare with findings from earlier tests performed by District personnel to identify the occurrence of a flow control change in the wet well transition zone, to determine correlations between the pressure data and the structural vibration data, and to evaluate and recommend operating procedures for the QC valves.

9. The objectives of this report are to present the results of the analysis of measured vibrations and pressures from the tests conducted during 1984 and 1985 and to document recommended operating procedures. The test facilities, equipment, and procedures are described in Part II. In Part III, the resulting analysis is presented and discussed. Part IV presents conclusions and recommendations.

Scope

10. Releases were made from the reservoir using various configurations of portal openings and QC valve openings. Discharges ranged from 150 cfs (one-valve operation) to 1,120 cfs (two-valve operation). Test measurements in the wet wells and intake tower included:

- a. Pressures in the transition zone of the wet wells upstream and downstream of the QC valve.
- b. Pressures at the entrance into the wet wells downstream of butterfly valves No. 9 and 10 (elevation 1,449.0 ft). This information was to be used for determination of flow effects and their relationship to dynamic response of the tower movement.
- c. Structural vibrations to determine the modal responses of the tower with and without flow releases.
- d. Observations of noises at the QC valves and operating portal butterfly valves which might indicate cavitation occurring, as well as other audible or visual observations.

PART II: TEST FACILITIES, EQUIPMENT, AND PROCEDURES

Test Facilities

Transition zone pressures

11. Four pressure transducers were mounted along the top centerline axis of each wet well transition zone. A 1-3/8-in.-diameter hole was drilled and tapped to accept the transducer adapter (Figure 3). The transducers were threaded into each hole from the topside of the wet well.

12. The transducers were designated as 1P1-1P4 for wet well No. 1 (located on the left of the intake tower when looking downstream) and 2P1-2P4 for wet well No. 2. The signal cables from each of these transducers were routed through the interior of the intake tower to the recording area. The locations of these transducers are shown in Figures 4 and 5.

Top of wet well pressures

13. Pressures in the top of each wet well directly opposite the entrance of portals 9 and 10 were measured with pressure transducers 1P5, 1P6, 2P5, and 2P6. The locations of these transducers and the mounting apparatus used are shown in Figures 6-8. A 6-in. square hole cut into the top plate of each wet well (elevation 1,456.0 ft) allowed installation of the apparatus. A cover plate and gasket were installed over the hole to provide a watertight seal. A view of the mounting system for pressure transducers 1P5 and 1P6 in wet well No. 1 is shown in Figure 9.

Wet well hydrostatic pressures

14. Two taps located downstream of the butterfly valves No. 3 and 4 (elevation 1,375.0 ft) were used to install pressure transducers for recording the hydrostatic pressure in each wet well. These pressures were used to give an indication of the change in water surface resulting from changing discharges in the wet wells. The pressure tap at butterfly valve No. 4 is shown in Figure 10.

Horizontal motions

15. The horizontal motion of the tower was measured using servo-accelerometers with sensitivities of 0.25 to 5.0 volts/g. These accelerometers were mounted on the intake tower at the eight elevations shown in Figures 11 and 12. Biaxial arrays of accelerometers were placed at elevations 1,515, 1,473, 1,444, 1,421, 1,394, 1,370, 1,337, and 1,289 ft. The base of the intake tower is at elevation 1,230 ft. A pendulum, used as a crude measuring device, showed what relative dynamic displacements of the tower could be observed by eye. The pendulum was a plumb bob on a 8-ft-long string hung near the top of the tower.

16. Figure 13 shows an accelerometer located at elevation 1,515 and Figure 14 shows the location of an accelerometer and pressure cells 1P5, 1P6, 2P5, and 2P6 at elevation 1,449 for the testing. The shaker locations are shown in Figure 13 for the low-level forced-vibration tests (the accelerometer locations were the same). In addition to the general hydraulic tests, the forced-vibration tests were conducted using the shaker to obtain data for more accurate estimates of the dynamic properties of the tower without the interference of the water-intake operations.

Test Equipment

17. The test equipment listed and described herein includes the transducers and recording equipment. Transducers used in the test were as follows:

- a. Wet well transition pressures: 100-psia pressure transducer.
- b. Portal jet pressures: 50-psia pressure transducers.
- c. Structural vibration sensors: 18 servo-accelerometers, sensitivities range from 0.25 volts/g to 5.0 volts/g.

18. The recording equipment consisted of (a) a WES-fabricated bridge amplifier system to condition transducer output signals, (b) a WES-fabricated calibration panel, (c) a Sangamo model Sabre V 32-track magnetic tape recorder, (d) Fluke model 8200A digital voltmeter and several oscilloscopes for periodic data checks during testing, and (e) a multichannel signal processor to perform real-time frequency spectral analysis of the data. Figure 15 shows the equipment setup at the recording area (elevation

1514.5 ft). The vibration equipment (used to conduct the low-level forced-vibration tests) consisted of a Zonic ES-302 inertial mass exciter (shaker) and a hydraulic power supply. The shaker was mounted to a steel base plate which was epoxied to the concrete at elevation 1514.5 ft. In Figure 16, the base plate to which the shaker was attached is shown. In Figure 17, the shaker is attached to the base plate. The hydraulic power supply is shown in Figure 18.

Test Procedures

19. Pressures and tower vibrations were measured during tests conducted from 22 to 26 April 1985. Eighteen tests were completed for the Bloomington Lake Intake Tower. For these measurements, the QC valves were varied in the number opened and the valve opening. Also, the number of portals operated were varied. An average of three tests was made each day. The QC valve settings used in each test and the corresponding discharge information provided by the District were as follows:

QC Valve Opening, ft	Discharge, cfs (per wet well)
1.0	150
2.0	310
2.2	340
2.4	375
2.5	400
2.6	425
2.7	450
2.8	475
2.9	500
3.0	525
3.1	550
Full (3.16)	560

20. The tests for which these valve settings were made to obtain the pressure and vibrational data and the conditions at the time of testing were as follows. (As shown, the pool elevation was essentially constant):

Test No.	April 1985 Date	Pool Elevation ft, msl*	Butterfly Valve(s) Operating	QC Valves Operating
1A1	22	1,468.06	9,10	1,2
1A2	23	1,468.14	9,10	1,2
2A	23	1,468.15	9	1
3A	23	1,468.16	10	2
4A	24	1,468.16	7,8	1,2
5A	24	1,468.17	7	1
6A	24	1,468.17	8	2
11A	25	1,468.18	5,6	1,2
7A	25	1,468.20	8,9,10	1,2
9A	25	1,468.20	2,9,10	1,2
10A**	25	1,468.18	9,10	1,2
13†	25	1,468.18	9,10	1,2
2B	25	1,468.18	9	1
3B	25	1,468.18	10	2
4B	25	1,468.18	7,8	1,2
5B	25	1,468.18	7	1
6B	25	1,468.18	8	2
11B	25	1,468.18	5,6	1,2

* Mean sea level.

** For this test, QC valve 1 was set at 1.0 ft, and QC valve 2 was set at full open.

† For these tests ("B" series), dynamic measurements were recorded at selected QC valve settings.

21. The procedure was generally the same for the above tests and consisted of the following:

a. Record test number, QC valve openings, date, and conditions.

b. Record step calibrations.

c. Record zero levels.

d. Fill wet wells.

e. Start recorder and raise QC valves simultaneously.

f. Stop valve at each opening listed in Tables 1-16 for approximately 1 minute.

g. Record data on tape.

h. Record pool elevation.

i. Repeat steps e-h for each valve opening.

22. Individual tests were recorded on magnetic tape for 15 minutes. Gain changes and calibrations were made as required during the test period.

PART III: TEST RESULTS AND ANALYSIS

Transition Zone Pressures

23. Tables 1-10 list the mean pressures and dynamic peak-to-peak pressures at all wet well transition zone pressure transducer locations as a function of QC valve opening. The pressures in wet well No. 1 are listed first followed by the pressures in wet well No. 2. These locations are identified in Figures 4 and 5. The values were scaled from oscillogram playbacks of the original analog data. As stated previously, one objective of these tests was to determine at what QC valve setting negative pressures occurred in the wet well transition zone, which might indicate that a potential for cavitation was present. In virtually all tests, transducer location P3 was the first transducer upstream of the QC valve to indicate negative pressures. All negative pressures at P3 occurred for QC valve openings greater than 2.9 ft.

Flow Control

24. A phenomenon that sometimes occurs during flow through a water quality release system such as that existing in the Bloomington Dam wet well is called a flow control change. This is the shift in the location of the point at which the flow is controlled. Intense vibrations and pressure fluctuations have been known to occur for operations within a narrow range of valve openings that separate the two flow control situations. In this study, recorded pressures indicate that for valve openings less than or equal to 2.9 ft the flow is controlled at the gate lip. At valve openings greater than 2.9 ft, the flow is controlled at the inside curvature of the wet well transition zone. Pressures recorded by transducers P2 and P3 indicate that this is occurring (see Figure 19). After the control change had occurred, the hydrostatic pressure upstream of the transition zone became constant indicating that maximum discharge had been obtained. This is indicated in the pressure data in Tables 1 through 10, particularly for pressure transducers P1 and P2, and the hydrostatic pressures listed in Tables 11 through 15 for QC valve openings greater than or equal to 3.0 ft.

25. This flow control change was evident in the earlier tests performed

by the District. A water-quality sampling tap located just upstream of the QC valves had been observed to suddenly change from outflowing water (positive pressure indication) to drawing air (negative pressure indication) at the same valve openings mentioned above, indicating that low pressure had developed as a result of the flow control change.

26. When the QC valve no longer controls the flow, it can be assumed that the maximum discharge capacity of the wet well has been reached for that set of conditions. As mentioned earlier, this was confirmed by the pressure data from transducers P1, P2, and the wet well hydrostatic pressures. However, when valve operations are required to close the QC valve from the full open position, the valve must reenter the flow and regain control. It was evident from the test data that when the QC valve lip entered the flow, it produced maximum instantaneous pressure surges of 20-40 psi and loud banging noises in the tower. This pressure surge was apparent from the data of transducers P1, P2, and P3 in each wet well. A typical example of this is shown in Figure 20. Note in the figure that pressure increases downward.

27. There are certain conditions within the flow (such as irregularities of the boundary, curved surfaces, etc.) in which the pressures within the system reach the vapor pressure of the liquid and can result in the formation of cavitation. Negative pressures greater than a vacuum of one-half atmosphere (-7.35 psi) can be considered to be indicators of potential cavitation (Rouse, 1949). Instantaneous pressures of this magnitude, and in some instances lower, were found to occur at transducers P3 and P4 for QC valve openings greater than 2.9 during tests 4A, 6A, 7A, 9A, and 11A (Tables 4, 6, 7, 8, and 9).

28. Based on observations made during the tests and from the pressure data listed in the tables, the flow control shifts and less severe negative pressures in the transition zone appear to occur during single portal operations which involve only the uppermost butterfly valves (valves No. 9 and 10). The lowest pressure recorded for these operating conditions was -2.2 psi at transducer 2P3 for test 1A2 (Table 1). Operation of these upper butterfly valves in combination with one or more of the lower butterfly valves in the same wet well lowered the pressure further to -7.8 psi at transducer 2P3 for

tests 7A and 9A. The lowest negative pressure of -13.0 psi was recorded at transducer 2P3 for a single butterfly valve operation (valve No. 8) during test 6A.

29. As the pressures in the wet well transition zone decreased with increasing QC valve opening, it was observed that the pressure fluctuations became significantly larger. This was particularly evident at transducers P3 and P4 for QC valve openings greater than 2.9 ft. It is conceivable that these increased pressure fluctuations in the transition zone could be the result of vapor cavities created in the flow and therefore could also be used as indicators of potential cavitation.

30. At the inception of the flow control, not only did the pressure fluctuations increase, but there was also an increase in localized vibration of the wet well transition zone conduit. As a result of the combination of these two conditions, the transducers at locations 1P3 and 1P4 were destroyed. This situation occurred for several tests, exhausting the supply of spare gages and, thus, explains the lack of data recorded at transducer 1P4.

31. The swiftness with which the flow control shift occurred and the small range of the QC valve openings (2.9-3.0 ft) over which the control change occurred were such that oscillations of the flow back and forth from the gate to the transition zone conduit could not develop and were not evident in the data analysis. Therefore, no correlation between the flow control shift and the tower movement could be made.

Upper Wet Well Pressures

32. Pressure transducers mounted on a special apparatus for lowering into the top of each wet well (as shown in Figures 6-9) were used to measure the dynamic pressures of the flow jets entering the wet well through butterfly valves No. 9 and 10 (elevation 1,449.0 ft). These pressures and pressure fluctuations are listed as follows for test 1A1:

Test 1A1

Pressure Cell	Type of Pressure	Pressures, in Feet of Water for QC Valve Opening, ft 1.0	2.0	2.2	2.4	2.5	2.6	2.7	2.8	2.9
1P5	Mean	19.7	15.7	6.6	0.0	0.0	0.0	0.0	0.0	0.0
	P-P*	0.0	22.5	26.3	26.3	33.0	26.3	33.0	33.0	35.5
1P6	Mean	20.5	13.6	13.6	6.9	6.9	3.0	0.0	0.0	0.0
	P-P	0.0	16.8	23.0	20.5	27.4	27.2	23.8	20.5	34.1
2P5	Mean	19.6	9.9	2.8	0.0	0.0	0.0	0.0	0.0	0.0
	P-P	0.0	19.8	26.3	12.9	13.1	16.3	19.6	14.3	23.7
2P6	Mean	20.3	10.2	5.1	0.0	0.0	0.0	0.0	0.0	0.0
	P-P	0.0	15.2	20.3	17.8	17.8	17.8	17.8	19.0	25.4

* Greatest instantaneous peak-to-peak pressure.

33. The oscillogram traces of the upper wet well pressures for test 1A1 were analyzed and revealed that low frequency pressure fluctuations existed in both wet wells. These fluctuations had a frequency of 0.3-0.8 Hz and were intermittent, occurring every 50 seconds. The surges began to appear when the QC valve opening reached 2.6 ft.

34. Only one test was performed with the special pressure transducer apparatus in place in each wet well. The failure of the seal at the wet well roof and instability of the apparatus in the turbulent flow at certain QC valve openings were the reasons for its limited application. It should be noted that at QC valve openings of 2.4 ft and greater, the apparatuses were experiencing a great deal of movement (rocking back and forth, side to side, etc.) and therefore, the data acquired for this test, at these QC valve openings, may be questionable. Due to the limited amount of time available for testing, no attempts were made to improve the stability of the apparatuses, and they were then removed from the wet wells. An attempt was made, however, to obtain pressure data at the top of the wet wells using the apparatus mounting hole cover plates. The mounting plates were drilled and tapped to accept a threaded pressure transducer mount. The cover plate and pressure tranducer were then installed on the top of the wet well at elevation 1,456.

35. The single transducers (1P5, 2P5) mounted in the top of each wet well were used to detect changes in water level in each wet well for the pool elevation and portals tested. The data recorded from these transducers

revealed low mean pressure readings at the 2.9 to 3.0 ft valve openings with slightly larger peak-to-peak pressure values indicating some surging of the water level may be occurring. However, these data did not correlate well with any of the water level data recorded within each wet well. It is possible that the surging that the transducers were responding to was, in effect, the surging of air in and out of the air vents which were very close in proximity to the transducer locations. This surging of the air in the air vents was quite audible and could be heard throughout the structure. In general, the accuracy of these transducers in providing the intended information is questionable.

Wet Well Hydrostatic Pressures

36. As mentioned earlier, pressure transducers located just downstream of butterfly valves No. 3 and 4 (elevation 1,375 ft) were used to monitor the change in water level in each wet well resulting from changing discharge. The data from each of these transducers are listed in Tables 11-15. From the information gathered, it was determined that the greatest change in water level (43.2 ft in wet well No. 1 during test 2A and 44.6 ft in wet well No. 2 during test 1A2 and 3A) occurred when only the upper butterfly valves (No. 9 and 10) in each wet well were open and the QC valve was at an opening of 3.0 ft or greater. The smallest change in water level (5.3 ft) with the QC valve at 3.0 ft opening or greater occurred during test 9A when there were two butterfly valves open in the same wet well. In this test, butterfly valve No. 10 (elevation 1,449 ft) and butterfly valve No. 2 (elevation 1,342.0 ft) of wet well No. 2 were open with the QC valve at a 3.0-ft opening. A more moderate drop in the wet well water surface (24-26 ft) was observed when butterfly valves other than valves No. 9 and 10 were operated.

37. The large drop in water level experienced during test 1A2 with only portals 9 and 10 open resulted in the water surface within the wet wells dropping below the invert of butterfly valves No. 9 and 10 (elevation 1,446.5 ft) for QC valve openings of 2.7 ft and greater. This resulted in unsubmerged flow at these portals. During the majority of the testing, loud noises were heard within the tower for many of the portal and QC valve opening combinations. However, the testing of butterfly valves No. 9 and 10 produced the lowest noise level of all the tests. This may be the result of the relatively

low water surface in the wet wells that created the unsubmerged flow conditions at the portals and eliminated any formation of unusual flow patterns (swirling, vortices, etc.).

38. Nonsteady flow conditions may be occurring in the wet wells as a result of the unsubmerged flow conditions, the intake bends, and/or possible butterfly valve alignment problems. If this is the case, the tower movement could be initiated by the forces created by these discharge fluctuations. A decrease in the movement of the tower was evident with the operation of portals at the lower elevations (below elevation 1,426.0 ft). During these tests, the water level within the wet wells was higher and the portals remained completely submerged. These observations all confirmed the observations noted from earlier tests performed by the District at various pool elevations.

39. Loud banging noises were heard in the tower during closure of the QC valves after being in the full open position and occurred at an opening of 2.9 ft. These same sounds were heard at the same point during tests run at lower and higher pool elevations. It was assumed that these sounds were made by the isolator rings banging within their bulkhead slots. The data analysis did not reveal any information that would indicate any unusual effects created by movement of the isolator rings. Some concern was expressed about the possibility of the isolator rings floating out of position if a sufficient pressure surge (greater than 0.7 psi) were present. The data obtained indicated that a significant pressure surge (20-40 psi) existed in the transition zone as the QC valve reentered the flow after operating at full open. This pressure surge may certainly have been transmitted upward through the wet well to the isolator rings and may have been associated with the loud banging noise heard while closing the valve. However, the data obtained would not indicate whether any movement of the isolator rings occurred or whether the isolator rings were out of position.

Structural Motions

40. In 1984, data from 72 tests were recorded. Each test lasted approximately 1 minute. Data from the 1-minute test contained random vibration response of the tower due to water flows through the intake conduits. Of the 72 tests, 6 recorded the response of the bridge and the

remaining 66 recorded the response of the tower at different QC gate openings. Data from three tests with the highest vibration levels were chosen for performing the modal analysis of the structure. Of these three tests, two had the top portals open and the third had one top portal and one bottom portal open.

41. The second series of tests, which this report describes in more detail, contained longer time records so that it would be possible to identify any changes in tower response between gate changes and correlate these changes with measured pressures. The tests conducted are summarized in Table 16. Also, Table 17 lists the forced-vibration tests for different combinations of full and empty wet well. These data can be used to assess possible effects on the frequency response of the tower above 4 Hz. Figure 21 shows a typical force spectrum of the shaker and the operating range for the forced-vibration tests. The ambient data from the first and the second tests were required to determine the natural frequencies of the responses of the tower below 4 Hz. The ambient tests were used to conduct the modal analysis. The acceleration data acquired was processed to compute the cross- and auto-spectrum functions. Also, coherence functions were computed giving an estimate of the signal-to-noise ratio. For ambient vibration measurements of this type, a modal analysis is conducted using cross- and auto-spectral density functions (Bendat and Piersol 1980). The cross-spectrum function provided the phase relationship between gages. The auto-spectrum function provided an estimate of the amplitude of the mode-shape vector. Thus, for a given natural frequency of the tower, responding in either bending or torsion, the relative displacement of the tower is determined from each accelerometer location.

42. Structural movements were monitored using accelerometers which were mounted at various elevations and oriented in the north-sourth and east-west planes of the intake tower. Tower movement was observed to occur when one or both of the upper butterfly valves (valves No. 9 and 10) were operated in each wet well. The movement was noticeably increased when QC valve openings increased from a range of 2.2 ft to 2.7 ft reaching a maximum at 3.0 ft opening. As previously discussed, the hydrostatic pressure measurements revealed a drop in the water level within the wet wells below the centerline elevation of the upper portals. This drop in water level allows for an unsubmerged flow condition to exist at these portals which is suspected to be the driving force

of the tower movement. The accelerometers revealed very strong responses to movement and were noted to be in the frequency ranges of 1.52 to 6.95 Hz. The tower movement was noticeably reduced during operation of the lower butterfly valves (valves No. 5-8) either alone or in combination with other valves possibly due to the existence of a higher water level in the wet well.

43. In Tables 18-20, examples of the resulting phase values and the estimates of the mode-shape vector amplitudes are listed. Also, the damping estimates from gage location are listed. In Figures 22-25, the bending mode and a torsional mode are shown. The modes occurred at frequencies of 1.52, 4.26, 6.88, and 6.95 Hz. It is seen that the view of mode in Figure 22 is a fundamental bending mode; in Figure 23, a second-order bending mode; in Figure 25, possibly a third-order bending mode of the tower in the north-south plane. A torsional mode is shown in Figure 24. For the modes shown, the damping estimates range from 0.32 to 1.8 percent of critical damping.

44. In Figure 26, a chart is shown which relates displacement, velocity, and acceleration for any observed frequency of harmonic motion. The maximum acceleration recorded by any measurement was equal to 0.01 g's. If the value of 0.01 g's is taken to be a conservative upper bound, then it is seen in Figure 26 that even for this level of acceleration at any frequency between 0.1 and 100.0 Hz that the level of vibration is not detrimental to the structure even though the motions perceived by personnel ranged from mildly noticeable to very uncomfortable. The cross-hatched area shown in Figure 26 was determined by the U.S. Bureau of Mines with the experience of blasting effects on nearby structures (concrete and block building) (Harris and Crede 1976). This chart has been used recently (Haynes 1986) to determine the safe response of a light pier, which is a tower structure subjected to ice loading.

45. To read the chart (Figure 26), assume that if a bending mode occurs at 1.0 Hz with a maximum acceleration level of 10 mg, then the peak dislacement would be equal to 0.1 in. Reading across to the vertical scale, the velocity is found to be equal to 0.6 in./sec. Thus, for any given harmonic response, the acceleration, velocity, and displacement are related at a particular frequency for the tower.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

46. From the observations and data obtained during the field tests, it was determined that a flow control shift does occur while opening the QC valves in each wet well. The pressure data reveals that the control point shifts from the QC valve to a point downstream of transducer location P2 at QC valve openings greater than 2.9 ft.

47. An extremely large pressure surge (20-40 psi) was evident at the point that the QC valve, after operating at full open, reenters the high-velocity flow and regains control. These surges are assumed to cause the loud bangs which could be associated with the isolator rings moving around in the bulkhead slots.

48. The pressure data at transducer locations P1 and P2 in the transition zone indicate that the pressures do not change once the control shift from the gate lip has taken place implying that maximum discharge capacity of the wet well has been attained at a gate opening of 2.9 ft.

49. Large drops in water level within each wet well (43-44 ft) occurred when only the upper portals were operated within each wet well. A more moderate drop in water surface (24-26 ft) occurred when one butterfly valve per wet well, below valves No. 9 and 10, was operated. Smaller drops in water level (5-18 ft) occurred when two portals were operated in a single wet well.

50. The damping estimates that were identified at the natural frequencies correspond very well with previous vibration tests conducted on the San Bernardino Tower in California (Rea, Liaw, and Chopra 1975). From the remaining data, it is possible to compute mean square values of acceleration for certain frequency ranges. The forced-vibration tests conducted on the Bloomington Intake Tower verified the modal responses determined from the ambient tests of the tower above 4 Hz.

51. From Figure 26, the vibration response of the tower is within safe limits assuming a conservative maximum acceleration level of 0.01 g's for all modes. However, no conclusions can be drawn concerning long-term effects of the cycling response of the tower.

52. Any effects of the isolator rings moving in the bulkhead slots could not be distinguished from the ambient response of the tower. To determine whether the isolator rings move would require that the rings be instrumented.

Recommendations

53. Operation of the lower portals decreased the tower movement significantly but at the same time, the noise level and negative pressures in the transition zone of each wet well were increased at QC valve openings of 2.9 ft and greater. It is recommended that for operation of the lower butterfly valves (those below elevation 1,449.0 ft) the QC valve openings be limited to a maximum of 2.9 ft to eliminate the cavitation-like noises, the negative pressures in the transition zone associated with the flow control, and the pressure surges created from the QC valve reentering the flow. An adjustable electrical limit switch can be installed on the QC valve operating mechanism to accomplish this. The decrease in discharge associated with limiting the valve opening is rather small and would not contribute significantly to flows released during emergency situations. Since a potential for cavitation may exist, it is also recommended that an inspection of the transition zone of each wet well be made by means of a borescope using the existing pressure transducer taps as access points for the instrument.

54. Horizontal tower movement is observed to occur when one or both of the highest buterfly valves (No. 9, 10) are operated alone in each wet well with the QC valve between a 2.2- and 2.7-ft opening. This movement is noticeably increased with increasing QC valve openings. For these operating conditions a drop in water level in the wet wells below the centerline elevation of the upper portals allows unsubmerged flow to exist at these portals which is suspected to be the driving force of the tower movement. Operation of lower butterfly valves (below elevation 1,449.0 ft), either alone or in combination with the upper valves, tends to reduce the tower movement by increasing the water level in each wet well. Therefore, it is recommended that QC valve openings be limited to 2.5 ft if only the upper butterfly valves (No. 9, 10) are operated to reduce the movement of the tower.

55. Because of the unusual geometry and complexity of the tower, it is recommended that an inspection be made to determine the flow patterns at the upper butterfly valves (No. 9, 10, and if possible, No. 7 and 8) as the flow enters the wet wells from the intakes. This could be accomplished with special photography from an observation hole in the lid of the wet well at elevation 1,456.0 ft (since there already exists a square cutout covered by a plate) or with a physical model study to accurately identify the hydraulic conditions

that exist in the prototype. The model study would also give valuable insight into recommendations of structural modifications that can alleviate most of the problems without restricting the capacity of the overall system.

56. The modal analysis of the acceleration measurements identified four major responses of the tower in a total of two bending planes. For the different tests, the bending responses were identified at different frequencies; however, the differences in these frequencies were not significant. The torsional mode frequency was identified as 6.88 Hz. The momentum forces of the intake flows, by themselves, contributed significantly to the vibration of the tower. It is recommended that both portals be opened at a given elevation during intake operations to minimize momentum loading effects.

57. A stress analysis was beyond the scope of this work, but it is recommended that a detailed stress analysis be performed. This can be accomplished with available finite-element computer programs. Stresses from the static and dynamic response can be analyzed. The stress analysis would help answer questions concerning the long-term effects of cyclic stresses on the tower.

58. At present, no structural changes (such as adding mass) are recommended. The vibration response of the tower is such that the limited gate openings will best control vibrations.

59. More detailed data analysis is recommended to determine the actual maximum acceleration level for each of the first three bending modes and the torsional mode (between 1.0 and 10.0 Hz).

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Table 1

Bloomington Dam

Test 1A2 Butterfly Valves No. 10 and 9 Open

Wet Well No. 1 Pressures, psi				QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
1P1	1P2	1P3	1P5			2P1	2P2	2P3	2P4	2P5
76.0	75.9	75.0	4.8	1.0	Mean values	72.9	74.3	70.9	0.0	4.4
-	-	-	1.2		Max. PK-PK	-	-	-	-	-
70.0	58.04	56.2	4.1	2.0	Mean values	68.3	58.7	54.7	-2.5	3.6
-	-	8.0	2.0		Max. PK-PK	-	-	-	2.28	2.6
67.5	53.6	51.5	3.4	2.2	Mean values	65.5	53.5	49.0	-3.6	3.6
-	-	8.0	2.7		Max. PK-PK	-	-	-	1.1	3.1
65.8	44.6	46.8	3.4	2.4	Mean values	63.6	45.2	42.4	-2.5	2.7
-	-	9.4	3.4		Max. PK-PK	-	-	-	1.4	3.5
64.1	43.9	42.2	3.4	2.5	Mean values	61.8	43.1	37.6	-2.5	2.7
-	-	9.4	4.0		Max. PK-PK	-	-	-	1.4	3.5
63.3	39.4	38.1	2.7	2.6	Mean values	59.0	37.9	35.8	-1.9	2.2
-	7.0	10.0	4.0		Max. PK-PK	-	10.4	9.5	1.1	3.5
61.6	35.0	33.4	2.7	2.7	Mean values	56.2	32.7	28.2	-1.4	1.8
-	8.0	11.0	4.1		Max. PK-PK	-	10.4	9.5	1.7	3.8
55.7	26.1	26.3	2.7	2.8	Mean values	52.5	22.3	18.6	-0.2	1.8
-	10.7	17.8	4.4		Max. PK-PK	-	10.4	14.2	1.4	3.6
50.6	17.2	9.4	2.0	2.9	Mean values	49.7	12.0	4.4	-0.2	1.8
-	13.4	27.2	4.4		Max. PK-PK	-	8.3	19.0	8.9	4.4
50.6	12.8	0.5	2.7	3.0	Mean values	45.0	9.8	-2.2	-0.2	1.8
-	15.3	18.7	5.8		Max. PK-PK	-	10.4	9.5	10.2	4.4
50.6	12.8	0.5	2.1	3.1	Mean values	45.0	9.8	-2.2	-1.9	1.8
-	12.8	18.7	5.8		Max. PK-PK	-	10.4	11.4	10.2	4.4
50.6	12.8	0.5	2.4	3.16	Mean values	45.0	9.8	-2.2	-1.9	1.8
-	12.8	18.7	6.8		Max. PK-PK	-	10.4	11.4	10.2	4.4

Table 2

Bloomington Dam
Test 2A, Butterfly Valve No. 9 Open

QC Valve Opening, ft		Wet Well No. 1 Pressures, psi			
		1P1	1P2	1P3	1P5
1.0	Mean values	75.9	75.2	75.6	4.4
	PK-PK	-	-	-	1.0
2.0	Mean values	69.2	59.9	59.6	3.4
	PK-PK	-	-	-	1.4
2.2	Mean values	67.5	52.9	54.1	2.7
	PK-PK	-	-	-	1.4
2.4	Mean values	65.0	45.6	47.4	2.5
	PK-PK	-	-	-	2.8
2.5	Mean values	62.4	43.9	42.8	2.0
	PK-PK	-	-	-	3.2
2.6	Mean values	62.4	39.6	38.0	2.0
	PK-PK	-	-	-	4.2
2.7	Mean values	60.8	35.1	33.3	2.0
	PK-PK	-	-	-	4.2
2.8	Mean values	56.6	26.2	28.6	2.0
	PK-PK	-	8.9	11.2	3.9
2.9	Mean values	50.7	17.2	14.6	1.3
	PK-PK	-	8.9	20.6	4.2
3.0	Mean values	48.2	12.8	-0.5	1.3
	PK-PK	-	10.7	14.1	4.5
3.1	Mean values	48.2	12.8	-0.5	1.3
	PK-PK	-	10.7	17.0	4.9
3.16	Mean values	48.2	12.8	-0.5	1.3
	PK-PK	-	13.3	18.3	6.3

Table 3

Bloomington Dam
Test 3A, Butterfly Valve No. 10 Open

QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
		2P1	2P2	2P3	2P4	2P5
1.0	Mean values	75.7	77.4	75.6	0.5	4.95
	PK-PK	-	-	-	0.6	-
2.0	Mean values	70.2	58.7	58.4	-0.7	10.5
	PK-PK	-	-	-	1.1	3.5
2.2	Mean values	66.4	53.5	51.8	-1.5	10.5
	PK-PK	-	-	-	2.3	7.0
2.4	Mean values	60.9	48.3	47.0	-2.0	10.5
	PK-PK	-	-	-	1.7	7.3
2.5	Mean values	59.0	43.1	42.3	-2.0	9.6
	PK-PK	-	-	9.5	2.3	6.1
2.6	Mean values	57.1	40.0	37.6	-2.6	9.6
	PK-PK	-	10.4	9.5	2.0	5.6
2.7	Mean values	54.4	35.8	32.8	-2.6	9.6
	PK-PK	-	12.5	9.5	2.3	4.4
2.8	Mean values	49.7	22.3	23.3	-1.5	5.3
	PK-PK	-	12.5	14.2	1.4	3.8
2.9	Mean values	45.0	11.9	9.05	-2.0	5.3
	PK-PK	-	15.6	19.0	7.4	3.8
3.0	Mean values	45.0	11.9	0.0	-2.0	5.3
	PK-PK	14.0	15.6	14.2	8.0	3.5
3.1	Mean values	45.0	11.9	0.0	-2.0	5.3
	PK-PK	-	15.6	14.2	10.3	4.4
3.16	Mean values	45.0	11.9	0.0	-2.0	1.8
	PK-PK	-	15.0	14.0	10.3	3.5

Table 4

Bloomington Dam

Test 4A, Butterfly Valves No. 8 and 7 Open

Wet Well No. 1 Pressures, psi				QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
1P1	1P2	1P3	1P5			2P1	2P2	2P3	2P4	2P5
77.6	74.2	76.5	5.0	1.0	Mean values	74.8	72.2	74.1	-0.2	5.0
-	-	-	1.4		PK-PK	-	-	-	0.6	0.8
70.9	59.1	59.6	4.3	2.0	Mean values	70.2	56.6	56.3	-1.4	3.9
-	-	-	1.7		PK-PK	-	-	-	3.0	1.7
69.2	54.6	54.9	3.9	2.2	Mean values	65.5	51.4	51.8	-2.6	3.6
-	-	9.4	1.7		PK-PK	-	-	-	3.0	1.7
67.5	47.6	48.3	3.6	2.4	Mean values	62.7	44.1	44.7	-3.8	3.3
-	-	9.4	1.4		PK-PK	-	-	-	1.0	1.7
65.0	44.0	42.7	3.3	2.5	Mean values	62.7	37.9	41.1	-3.2	3.3
-	-	9.4	1.4		PK-PK	-	8.3	-	1.2	1.7
64.8	38.7	40.8	3.3	2.6	Mean values	59.0	35.8	35.8	-3.2	3.8
-	-	11.3	1.4		PK-PK	-	5.2	7.1	1.0	1.7
62.5	34.2	33.3	2.9	2.7	Mean values	56.2	30.6	29.6	-2.6	2.8
-	-	11.3	2.1		PK-PK	-	8.3	8.0	0.9	2.0
58.5	28.0	26.7	2.5	2.8	Mean values	51.6	23.3	23.3	-1.8	1.9
-	-	14.1	2.1		PK-PK	-	9.4	7.1	1.0	2.0
58.3	12.8	9.9	1.5	2.9	Mean values	46.9	9.82	11.8	-0.6	1.6
-	-	23.5	2.5		PK-PK	-	10.4	10.6	2.4	3.0
54.1	3.9	- 8.9*	1.5	3.0	Mean values	44.1	4.5	-8.6	-7.2	1.0
-	-	-	4.2		PK-PK	-	9.4	-	14.5	2.9
54.1	3.9	gage	1.5	3.1	Mean values	44.1	4.5	-8.6	-7.2	1.0
-	-	out	4.2		PK-PK	-	9.4	-	14.5	3.4
54.1	3.9	gage	1.5	3.16	Mean values	44.1	4.5	-8.6	-7.2	1.0
-	-	out	4.2		PK-PK	-	9.4	-	14.5	4.25

*Transducer 1P3 went out shorting after reaching 3.0 ft open.

Table 5

Bloomington Dam
Test 5A, Butterfly Valve No. 7 Open

Wet Well No. 1 Pressures, psi				QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
1P1	1P2	1P3	1P5			2P1	2P2	2P3	2P4	2P5
77.0	76.0	72.8	4.5	1.0	Mean values	77.7	79.5	80.4	0.00	5.3
-	-	-	-		PK-PK					
71.8	61.7	61.6	3.5	2.0	Mean values				-1.0	
-	-	-	-		PK-PK				1.2	
69.3	57.2	56.9	3.1	2.2	Mean values				-1.2	
-	-	11.3	1.7		PK-PK				1.2	
66.8	51.0	47.5	2.8	2.4	Mean values				-1.2	
-	-	11.3	1.7		PK-PK				1.2	
65.9	48.4	42.8	2.8	2.5	Mean values				-1.6	
-	-	11.3	2.1		PK-PK				1.4	
65.1	43.9	38.1	2.5	2.6	Mean values				-1.6	
-	-	14.1	2.1		PK-PK				1.4	
63.4	39.4	33.4	2.4	2.7	Mean values				-1.6	
-	-	17.9	2.1		PK-PK				1.8	
60.9	30.6	24.0	2.2	2.8	Mean values				-1.6	
-	-	18.8	2.0		PK-PK				2.4	
56.7	17.2	9.9	2.1	2.9	Mean values				-1.6	
-	-	20.7	4.9		PK-PK				3.4	
55.0	12.8	-0.05	1.2	3.0	Mean values				-1.6	5.3
-	8.9	-	-		PK-PK				2.4	
55.0	12.8	gage	1.2	3.1	Mean values				-1.6	5.3
-	8.4	out	-		PK-PK				2.6	5.1
55.0	12.8	gage	1.2	3.16	Mean values				-1.6	5.3
-	8.9	out	-		PK-PK				2.4	3.7

NOTE: No flow through No. 2.
* Last reading before transducer went out during test at control shaft.

Table 6

Bloomington Dam
Test 6A, Butterfly Valve No. 8 Open

QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
		2P1	2P2	2P3	2P4	2P5
1.0	Mean values	75.8	73.3	76.0	-0.2	4.6
	PK-PK	-	-	-	0.6	-
2.0	Mean values	71.2	58.7	59.9	-1.2	4.1
	PK-PK	-	-	-	1.2	2.0
2.2	Mean values	68.4	52.5	56.4	-1.2	3.6
	PK-PK	-	-	-	1.7	1.7
2.4	Mean values	66.5	45.2	47.5	-1.4	3.3
	PK-PK	-	-	-	1.8	1.7
2.5	Mean values	64.7	42.1	42.1	-1.4	2.4
	PK-PK	-	-	-	1.1	2.0
2.6	Mean values	61.9	37.9	38.6	-1.4	2.4
	PK-PK	-	7.3	7.1	1.2	1.7
2.7	Mean values	59.1	31.7	33.2	-2.0	2.4
	PK-PK	-	9.4	8.9	1.4	1.9
2.8	Mean values	57.2	24.4	24.4	-2.0	1.9
	PK-PK	-	9.4	8.9	1.2	2.0
2.9	Mean values	52.6	10.9	11.9	-2.0	1.2
	PK-PK	-	10.4	8.9	2.0	3.7
3.0	Mean values	49.8	4.5	-13.0	gage	0.7
	PK-PK	-	10.4	-	out*	3.4
3.1	Mean values	49.8	4.5	-13.0	gage	0.7
	PK-PK	-	10.4	-	out	3.4
3.16	Mean values	49.8	4.5	-13.0	gage	0.7
	PK-PK	-	10.4	-	out	3.4

* Transducer 2P4 went out when opened from 2.9 to 3.0 ft.

Table 7

Bloomington Dam
Test 11A, Butterfly Valves No. 6 and 5 Open

Wet Well No. 1 Pressures, psi				QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
1P1	1P2	1P3	1P5			2P1	2P2	2P3	2P4	2P5
75.2	73.4	74.8	5.0	1.0	Mean values	75.8	73.5	72.4	0.0	4.9
-	-	-	-		PK-PK	-	-	-	-	1.4
71.8	57.2	56.8	4.3	2.0	Mean values	74.0	59.5	58.8	-0.5	3.9
-	-	-	-		PK-PK	-	-	-	3.0	1.7
69.3	52.9	51.2	3.6	2.2	Mean values	71.2	53.5	53.0	-3.0	3.9
-	-	-	-		PK-PK	-	-	-	2.5	1.7
66.8	43.9	45.0	3.3	2.4	Mean values	71.2	46.5	46.1	-3.0	3.2
-	-	-	-		PK-PK	-	-	-	1.2	1.7
65.1	39.4	39.1	2.9	2.5	Mean values	68.4	41.5	41.2	-2.5	2.5
-	-	-	-		PK-PK	-	-	-	1.2	1.7
65.1	35.0	33.2	2.9	2.6	Mean values	66.5	39.5	36.3	-1.8	2.5
-	-	-	-		PK-PK	-	-	-	1.2	2.1
63.4	32.3	29.7	2.9	2.7	Mean values	64.7	33.5	33.4	-1.8	2.5
-	-	-	-		PK-PK	-	-	-	1.2	1.7
60.9	26.1	21.4	2.2	2.8	Mean values	61.9	26.5	26.5	-1.0	1.8
-	-	17.7	2.5		PK-PK	-	-	9.2	-	2.8
56.7	12.8	9.6	1.5	2.9	Mean values	57.2	16.5	11.8	-0.5	1.1
-	-	16.5	2.8		PK-PK	-	10.0	7.8	1.2	4.2
55.C	5.6	-8.1*	0.8	3.0	Mean values	55.4	2.5	-12.7	-6.8	0.4
-	-	-	1.7**		PK-PK	7.4	10.0	-	16.0	7.7
55.0	8.4	gage	0.8	3.1	Mean values	55.4	2.5	-12.7	-6.8	0.4
-	-	out	1.7		PK-PK	7.4	10.0	-	16.0	5.9
55.0	8.4	gage	0.8	3.16	Mean values	55.4	2.5	-12.7	-6.8	0.4
-	-	out	1.7		PK-PK	7.4	10.0	-	16.0	9.1

*Transducer went out shortly before reaching 3.0 ft open.
**Low frequency fluctuations, surging ≈ 2Hz.

Table 8

Bloomington Dam
Test 7A, Butterfly Valves No. 10, 9, and 8 Open

Wet Well No. 1 Pressures, psi				QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
1P1	1P2	1P3	1P5			2P1	2P2	2P3	2P4	2P5
77.7	77.8	out	6.7 (surge in pressure)	1.0	Mean values	73.0	74.5	77.5	-0.5	5.3
-	-				PK-PK	-	-	-	-	1.7
71.0	60.0	out	4.6	2.0	Mean values	74.9	59.5	60.8	-3.0	6.0
-	-		1.7		PK-PK	-	-	-	2.5	1.4
69.3	52.9	out	3.6	2.2	Mean values	68.4	54.5	57.8	-3.0	5.3
-	-		3.0		PK-PK	-	-	-	2.5	1.4
67.62	45.8	out	3.2	2.4	Mean values	66.5	49.5	51.0	-3.0	4.6
-	-		4.2		PK-PK	-	-	-	2.5	1.4
65.1	44.0	out	3.2	2.5	Mean values	66.5	44.5	48.1	-2.5	4.6
-	-		3.0		PK-PK	-	-	-	1.2	1.4
65.1	39.6	out	3.2	2.6	Mean values	63.8	39.5	44.1	-2.5	4.6
-	-		4.2		PK-PK	-	-	-	1.2	2.1
62.6	35.1	out	2.5	2.7	Mean values	63.8	36.5	38.3	-1.8	4.6
-	-		3.9		PK-PK	-	-	-	2.0	2.4
59.2	28.0	out	2.5	2.8	Mean values	61.0	29.5	31.4	-1.0	4.6
-	-		3.5		PK-PK	-	-	-	1.2	2.8
54.2	17.3	out	2.5	2.9	Mean values	59.1	16.5	16.7	-0.5	3.9
-	-		5.6		PK-PK	-	-	-	1.2	2.1
52.5	12.8	out	2.22	3.0	Mean values	57.2	6.5	-7.8	-5.5	3.9
-	-		6.7		PK-PK	-	-	-	2.0	1.4
52.5	12.8	out	1.8	3.1	Mean values	57.2	6.5	-7.8	-5.5	3.9
-	-		5.9		PK-PK	-	-	-	22.5	1.4
52.5	12.8	out	1.8	3.16	Mean values	57.2	6.5	-7.8	-5.5	3.9
-	-		5.9		PK-PK	-	-	-	22.5	1.4

Table 9

Bloomington Dam
Test 9A, Butterfly Valves No. 10, 9, and 2 Open

Wet Well No. 1 Pressures, psi				QC Valve Opening, ft		Wet Well No. 2 Pressures, psi				
1P1	1P2	1P3	1P5			2P1	2P2	2P3	2P4	2P5
77.7	79.6	out	5.0	1.0	Mean values	74.9	74.5	77.5	-0.5	5.3
-	-		1.1		PK-PK	-	-	-	-	1.4
71.0	60.0	out	3.9	2.0	Mean values	73.0	59.5	60.8	-3.0	4.9
-	-		1.4		PK-PK	-	-	-	2.5	1.3
69.3	52.9	out	3.2	2.2	Mean values	71.2	54.5	57.8	-3.0	4.9
-	-		3.5		PK-PK	-	-	-	2.5	1.4
67.6	48.5	out	3.2	2.4	Mean values	71.2	49.5	51.0	-3.0	4.6
-	-		3.9		PK-PK	-	-	-	1.5	1.4
65.1	44.0	out	2.8	2.5	Mean values	68.4	44.5	48.0	-3.0	4.6
-	-		3.9		PK-PK	-	-	-	1.2	1.1
65.1	39.6	out	2.5	2.6	Mean values	68.4	39.5	44.1	-3.0	4.6
-	-		4.5		PK-PK	-	-	-	1.2	1.4
62.6	35.1	out	2.5	2.7	Mean values	68.4	34.5	38.3	-1.8	4.6
-	-		4.9		PK-PK	-	-	-	1.2	1.4
60.9	28.0	out	2.4	2.8	Mean values	63.8	29.5	31.4	-1.8	4.6
-	-		3.8		PK-PK	-	-	-	1.2	1.4
54.2	17.3	out	1.8	2.9	Mean values	61.9	19.5	16.7	-0.5	4.6
-	-		5.5		PK-PK	-	-	-	2.5	2.8
52.5	12.9	out	1.8	3.0	Mean values	59.1	6.5	-7.8	-3.0	4.6
-	-		4.2		PK-PK	-	-	-	20.0	0.7
52.5	12.9	out	1.8	3.1	Mean values	59.1	6.5	-7.8	gage	4.6
-	-		4.9		PK-PK	-	-	-	out	1.1
52.5	12.9	out	1.8	3.16	Mean values	59.1	6.5	-7.8	gage	4.6
-	-		4.9		PK-PK	-	-	-	out	1.1

Table 10

Bloomington Dam,
Tests 10A, 1B, 2B, 3B, 4B, 5B, 6B, 11B

Butterfly Valves 10 and 9 Open

	QC Valve Opening, ft		Wet Well Pressures, psi 1P2	1P5	2P1	2P2	2P3	2P5
Test 10A	1.0	Mean values	72.6	5.0	-	-	-	-
		PK-PK	-	-				
	3.16	Mean values			45.7	9.0	-2.7	1.5
		PK-PK			10.1	10.6	10.0	4.9
		Dynamic Pressure Measurements						
Test 1B	1&2 full	PK-PK	11.9	4.9	10.1	10.6	10.0	4.9
Test 2B	1 full	PK-PK	14.9	5.4	-	-	-	-
Test 3B	2 full	PK-PK	-	-	12.6	10.6	20.2	4.6
Test 1B1	1&2 full	PK-PK	0.7	4.6	12.6	13.2	22.0	4.6
		Butterfly Valves No. 8 and 7 Open						
Test 4B	1&2 full	PK-PK	5.0	3.1	8.4	10.6	7.6	1.6
Test 5B	1 full	PK-PK	5.1	4.6	-	-	-	-
Test 6B	2 full	PK-PK	-	-	10.1	8.8	6.8	1.6
		Butterfly Valves No. 6 and 5 Open						
Test 11B	1&2 3.16	PK-PK	4.3	1.5	6.7	7.0	5.1	2.5

Table 11

WET WELL WATER SURFACE ELEVATIONS
PRESSURE SENSORS IN PORTALS 3 AND 4, TESTS 1A2 AND 2A

Test No.	Time minutes	Butterfly Valve No.	QC Valve Setting ft	Water Surface Elevation, ft Portal 3	Portal 4
Quiet	3		0	0.0	6.6
1A2	1	9, 10	0	1,468.0	1,468.0
			1.0	1,462.7	1,463.8
			2.0	1,455.8	1,456.0
			2.2	1,454.0	1,454.4
			2.4	1,450.0	1,451.1
			2.5	1,448.8	1,450.0
			2.6	1,448.0	1,448.4
			2.7	1,446.5	1,445.4
			2.8	1,439.6	1,436.1
			2.9	1,428.1	1,424.6
			3.0	1,425.8	1,423.4
			3.1	1,425.8	1,423.4
			3.16	1,425.8	1,423.4
2A	1	9	0	1,468.0	0.0
			1.0	1,461.5	0.0
			2.0	1,453.4	0.0
			2.2	1,451.1	0.0
			2.4	1,448.8	0.0
			2.5	1,447.0	0.0
			2.6	1,445.1	0.0
			2.7	1,443.5	0.0
			2.8	1,438.5	0.0
			2.9	1,426.9	0.0
			3.0	1,424.8	0.0
			3.1	1,424.8	0.0
			3.16	1,424.8	0.0

Table 12

WET WELL WATER SURFACE ELEVATIONS
PRESSURE SENSORS IN PORTALS 3 AND 4, TESTS 3A AND 4A

Test No.	Time minutes	Butterfly Valve No.	QC Valve Setting ft	Water Surface Elevation, ft Portal 3	Water Surface Elevation, ft Portal 4
3A	1	10	0	0.0	1,468.0
			1.0	0.0	1,464.0
			2.0	0.0	1,456.9
			2.2	0.0	1,453.9
			2.4	0.0	1,451.1
			2.5	0.0	1,449.3
			2.6	0.0	1,447.7
			2.7	0.0	1,445.4
			2.8	0.0	1,435.0
			2.9	0.0	1,426.7
			3.0	0.0	1,423.4
			3.10	0.0	1,423.4
			3.16	0.0	1,423.4
4A	1	7, 8	0	1,468.0	1,468.0
			1.0	1,462.4	1,465.0
			2.0	1,457.2	1,460.6
			2.2	1,456.0	1,458.5
			2.4	1,453.1	1,456.9
			2.5	1,452.8	1,455.7
			2.6	1,451.8	1,454.6
			2.7	1,450.4	1,453.0
			2.8	1,448.8	1,451.1
			2.9	1,444.7	1,448.6
			3.0	1,443.0	1,444.2
			3.1	1,443.0	1,444.2
			3.16	1,443.0	1,444.2

Table 13

WET WELL WATER SURFACE ELEVATIONS
PRESSURE SENSORS IN PORTALS 3 AND 4, TESTS 5A AND 6A

Test No.	Time minutes	Butterfly Valve No.	QC Valve Setting ft	Water Surface Elevation, ft Portal 3	Portal 4
5A	1	7	0	1,468.0	1,468.0
	(Wet Well #2 Full)		1.0	1,462.2	1,468.0
			2.0	1,458.0	1,468.0
			2.2	1,456.2	1,468.0
			2.4	1,454.6	1,468.0
			2.5	1,453.4	1,468.0
			2.6	1,451.8	1,468.0
			2.7	1,450.7	1,468.0
			2.8	1,448.8	1,468.0
			2.9	1,444.9	1,468.0
			3.0	1,442.8	1,468.0
			3.1	1,442.8	1,468.0
			3.16	1,442.8	1,468.0
6A	1	8	0	1,468.0	1,468.0
	(Wet Well #1 Full)		1.0	1,468.0	1,465.4
			2.0	1,468.0	1,460.8
			2.2	1,468.0	1,459.2
			2.4	1,468.0	1,457.4
			2.5	1,468.0	1,456.0
			2.6	1,468.0	1,455.0
			2.7	1,468.0	1,453.0
			2.8	1,468.0	1,451.1
			2.9	1,468.0	1,447.2
			3.0	1,468.0	1,444.2
			3.1	1,468.0	1,444.2
			3.16	1,468.0	1,444.2

Table 14

WET WELL WATER SURFACE ELEVATIONS
PRESSURE SENSORS IN PORTALS 3 AND 4, TESTS 9A AND 10A

Test No.	Time minutes	Butterfly Valve No.	QC Valve Setting ft	Water Surface Elevation, ft Portal 3	Portal 4
9A	1	2, 9, 10	0	1,468.0	1,468.0
			1.0	1,461.2	1,466.4
			2.0	1,453.4	1,465.4
			2.2	1,451.1	1,464.8
			2.4	1,448.8	1,464.7
			2.5	1,446.5	1,464.3
			2.6	1,445.3	1,464.0
			2.7	1,444.2	1,464.0
			2.8	1,438.4	1,463.6
			2.9	1,428.1	1,462.9
			3.0	1,425.8	1,462.7
			3.1	1,425.8	1,462.7
			3.16	1,425.8	1,462.7
10A	1	9, 10	QC1 @ 1	1,460.5	1,423.4
	2		QC2 @ 3.15	1,460.5	1,423.4
	3			1,460.5	1,423.4
	4				
	1		QC @ 2	1,424.6	1,423.4
	2		3.16	1,424.6	1,423.4
	3			1,424.6	1,423.4

Table 15

WET WELL WATER SURFACE ELEVATIONS
PRESSURE SENSORS IN PORTALS 3 AND 4, TESTS 11A AND 7A

Test No.	Time minutes	Butterfly Valve No.	QC Valve Setting ft	Indicator RDG Portal 3	Indicator RDG Portal 4
11A	1	5, 6	0	1,468.0	1,468.0
			1.0	1,462.4	1,465.4
			2.0	1,458.0	1,461.0
			2.2	1,456.2	1,458.7
			2.4	1,454.4	1,456.9
			2.5	1,458.0	1,455.7
			2.6	1,453.4	1,454.6
			2.7	1,450.7	1,453.0
			2.8	1,448.4	1,450.9
			2.9	1,445.1	1,447.4
			3.0	1,443.5	1,444.2
			3.1	1,443.5	1,444.2
			3.16	1,443.5	1,444.2
7A	1	8, 9, 10	0	1,468.0	1,468.0
			1.0	1,461.3	1,465.7
			2.0	1,453.4	1,462.7
			2.2	1,451.1	1,461.0
			2.4	1,448.6	1,459.4
			2.5	1,447.7	1,458.7
			2.6	1,445.1	1,458.0
			2.7	1,443.5	1,457.1
			2.8	1,439.6	1,455.8
			2.9	1,428.1	1,453.0
			3.0	1,425.8	1,450.2
			3.1	1,425.8	1,450.2
			3.16	1,425.8	1,450.2

Table 16

Summary of Tests

Test No.	Type	Butterfly Valve (s) Open	Quality Control Gate Settings, ft 1.0	2.0	2.2	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.16
1A	OBS	9, 10	All										
1B	AMB									*			*
2A	OBS	9	All										
2B	AMB												*
3A	OBS	10	All										
3B	AMB									*			*
4A	OBS	7, 8	All										
4B	AMB										*		
5A	OBS	7	All										
5B	AMB										*		
6A	OBS	8	All										
6B	AMB										*		
7A	OBS	8, 9, 10	All										
9A	OBS	2, 9, 10	All										
10A	OBS	9, 10	QC 1 @ 1.0 ft; QC 2 @ 3.16 ft (4 minutes)										
11A	OBS	5, 6	All										
11B	AMB										*		
13B	AMB	None--Transient responses											

NOTE: Observation (OBS, 0) runs go through all gate openings unless otherwise noted.
* Denotes 5-minute records of Ambient (AMB, A) data at specified gate openings.

Table 17

Forced Vibration Tests

Exciter Location*	Test No.	Orientation of Exciter	Wet Well No. 1	Wet Well No. 2
No. 1	FV-1	N	Empty	Empty
	FV-2	N	Empty	Empty
	FV-3	N	Full	Full
	FV-4	N	Full	Empty
	FV-5	N 45° E	Full	Full
	FV-6	E	Full	Full
	FV-7	E	Empty	Full
	FV-8	E	Full	Empty
	FV-9	E	Empty	Empty
No. 2	FV-10	N	Empty	Empty
	FV-11	N	Full	Empty
	FV-12	N	Empty	Full
	FV-13	N	Full	Full
	FV-14	W	Full	Full

* Exciter locations:
No. 1: Located at centerline of tower elevation 1,514.5 ft.
No. 2: West end of tower elevation 1,514.5 ft.

Table 18

Example of Values for Mode Shapes and Damping Ratios

Test Channel	1.523 Hz g^2/Hz Gyy	1.523 Hz ϕ	1.523 Hz Phase	4.26 Hz Gyy	4.26 Hz ϕ	4.26 Hz Phase	6.95 Hz Gyy	6.95 Hz ϕ	6.95 Hz Phase
1	1.0×10^{-5}	3.76×10^{-3}	Ref.	6.0×10^{6}	2.45×10^{-3}	Ref.	1.3×10^{-7}	3.61×10^{-4}	Ref.
2	1.0×10^{-5}	3.16×10^{-3}	-181°	3.0×10^{6}	1.73×10^{-3}	-181°	1.3×10^{-8}	1.14×10^{-4}	-187°
3	4.0×10^{-6}	2.0×10^{-3}	-181°	1.3×10^{6}	1.14×10^{-3}	-5.6°	1.3×10^{-6}	1.14×10^{-3}	-165°
4	1.9×10^{-6}	1.38×10^{-3}	-181°	3.0×10^{6}	1.73×10^{-3}	-4.9°	1.3×10^{-6}	1.14×10^{-3}	-166°
5	6.0×10^{-7}	0.775×10^{-3}	-178°	3.0×10^{6}	1.73×10^{-3}	-5.1°	6.0×10^{-7}	7.75×10^{-4}	-167°
6	2.9×10^{-7}	0.539×10^{-3}	-178°	3.0×10^{6}	1.73×10^{-3}	-5.6°	4.0×10^{-7}	6.32×10^{-4}	-170°
7	1.3×10^{-7}	0.361×10^{-3}	-176°	1.25×10^{6}	0.354×10^{-3}	-5.5°	1.3×10^{-7}	3.61×10^{-4}	-171°

Normalized ϕ	1.52 Hz	1.80 Hz	4.26 Hz	6.95 Hz
1	1.0		1.0	1.0
2	1.0		0.706	0.316
3	0.633		-0.465	0.316
4	0.437		-0.706	0.316
5	0.245		-0.706	2.15
6	0.171		-0.706	1.75
7	0.114		-0.141	1.0

Damping Estimates

ζ_1	Location	ζ_2	Location	ζ_3	Location
$0.040 = \frac{-0.123}{(2)\ (1.52)}$	1	$0.0058 = \frac{0.0492}{(2)\ (4.26)}$	1	$0.0088 = \frac{0.123}{(2)\ (6.95)}$	1
$0.032 = \frac{0.0984}{(2)\ (1.52)}$	5	$0.0058 = \frac{0.0492}{(2)\ (4.26)}$	5	$0.0071 = \frac{0.0984}{(2)\ (6.95)}$	5
$0.032 = \frac{0.0984}{(2)\ (1.52)}$	6	$0.0058 = \frac{0.0492}{(2)\ (4.26)}$	6	$0.0071 = \frac{0.0984}{(2)\ (6.95)}$	6
$0.032 = \frac{0.0984}{(2)\ (1.52)}$	7	$0.0058 = \frac{0.0492}{(2)\ (4.26)}$	7	0.0071	7

Table 19

Examples of Values for Mode Shapes and Damping Ratios

Test Channel	g^2/Hz Gyy (1.71 Hz)	1.71 Hz ϕ	1.71 Hz Phase	5.51 Hz Gyy	5.51 Hz ϕ	5.51 Hz Phase	6.88 Hz Gyy	6.88 Hz ϕ	6.88 Hz Phase
1	7×10^{-5}	0.00837	-180	8.0×10^{-6}	0.00400	0	3.03×10^{-5}	0.00550	0
2	6×10^{-5}	0.00775	0	8.0×10^{-6}	0.00400	-180	2.37×10^{-5}	0.00487	0
3	1.71×10^{-5}	0.00414	Reference	5.0×10^{-6}	0.00224	Reference	5.3×10^{-7}	0.000728	Reference
4	9.0×10^{-6}	0.00300	0	6.46×10^{-6}	0.00254	0	3.25×10^{-7}	0.000570	0
5	3.0×10^{-6}	0.00173	0	6.0×10^{-6}	0.00245	0	1.3×10^{-7}	0.000361	0
6	1.3×10^{-6}	0.00114	0	6.0×10^{-6}	0.00245	0	1.15×10^{-7}	0.000339	0
7	4.0×10^{-7}	0.000632	0	2.6×10^{-6}	0.00161	0	--	--	0

Normalized

ϕ	1.71 Hz	5.51 Hz	6.88 Hz
1	1.0	-1.0	-1.0
2	0.93	-1.0	0.89
3	0.49	0.56	0.13
4	0.36	0.64	0.10
5	0.21	0.61	0.066
6	0.14	0.61	0.062
7	0.076	0.40	--

Damping Estimates

ζ_1	Location	ζ_2	Location	ζ_3	Location
$0.029 = \frac{0.0984}{(2)\ (1.71)}$	1	$0.011 = \frac{0.123}{(2)\ (5.51)}$	1	$0.0072 = \frac{0.0984}{(2)\ (6.88)}$	1
0.029	2	0.011	2	0.0072	2
0.029	3	$0.0089 = \frac{0.0984}{(2)\ (5.51)}$	3	0.0072	3
0.029	4	0.0089	4	0.0072	4
0.029	5	0.0089	5	0.013	5
0.029	6	0.0089	6	$0.013 = \frac{0.1722}{(2)\ (6.88)}$	6
0.029	7	0.0089	7		7

Table 20

Example of Values for Mode Shapes and Damping Ratios

Test Channel	g^2/Hz Gyy	1.797 Hz ϕ	1.797 Hz Phase	5.43 Hz Gyy	5.43 Hz ϕ	5.43 Hz Phase	6.875 Hz Gyy	6.875 Hz ϕ	6.875 Hz Phase
1	1.1×10^{-5}	0.00332	-180°	4.0×10^{-6}	0.00200	-356°	5.0×10^{-6}	0.00224	0
2	1.0×10^{-5}	0.00316	-1°	2.1×10^{-6}	0.00145	-184°	4.0×10^{-6}	0.00200	0
3	1.14×10^{-5}	0.00338	Reference	8.0×10^{-6}	0.00283	Reference	3.53×10^{-7}	0.000594	Reference
4	1.3×10^{-6}	0.00114	0°	2.4×10^{-6}	0.00155	0°	5.0×10^{-8}	0.000224	0
5	4.5×10^{-7}	0.000671	-1°	2.2×10^{-6}	0.00148	-1°	3.5×10^{-8}	0.000187	0
6	2.0×10^{-7}	0.000447	-1°	2.2×10^{-6}	0.00148	-1°	--	0.000187	0
7	6.0×10^{-8}	0.000245	-2°	1.0×10^{-6}	0.00100	-2°	--	--	0

Normalized

ϕ	1.797 Hz	5.43 Hz	6.875 Hz
1	1.0	1.0	1.0
2	0.95	0.73	0.89
3	1.0	1.42	0.27
4	0.34	0.78	0.10
5	0.020	0.74	0.083
6	0.013	0.74	0.083
7	0.074	0.50	--

Damping Estimates

ζ_1	Location	ζ_2	Location	ζ_3	Location
$0.027 = \frac{0.0984}{(2)\ (1.82)}$	1	$0.011 = \frac{0.123}{(2)\ (5.43)}$	1	$0.0089 = \frac{0.123}{(2)\ (6.88)}$	1
0.027	2	$0.018 = \frac{0.1968}{(2)\ (5.43)}$	2	0.0089	2
0.027	3	0.011	3	0.0089	3
0.027	4	0.018	4	0.0089	4
0.027	5	$0.014 = \frac{0.1476}{(2)\ (5.43)}$	5	$0.014 = \frac{0.1968}{(2(\ (6.88)}$	5
0.027	6	0.014	6	$0.013 = \frac{0.1722}{(2)\ (6.88)}$	6
0.027	7	0.011	7	--	7

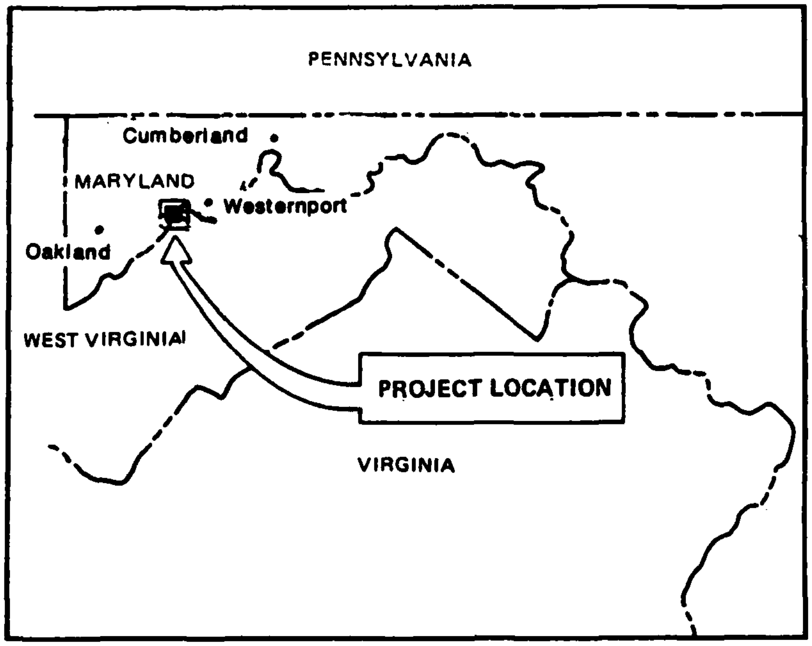
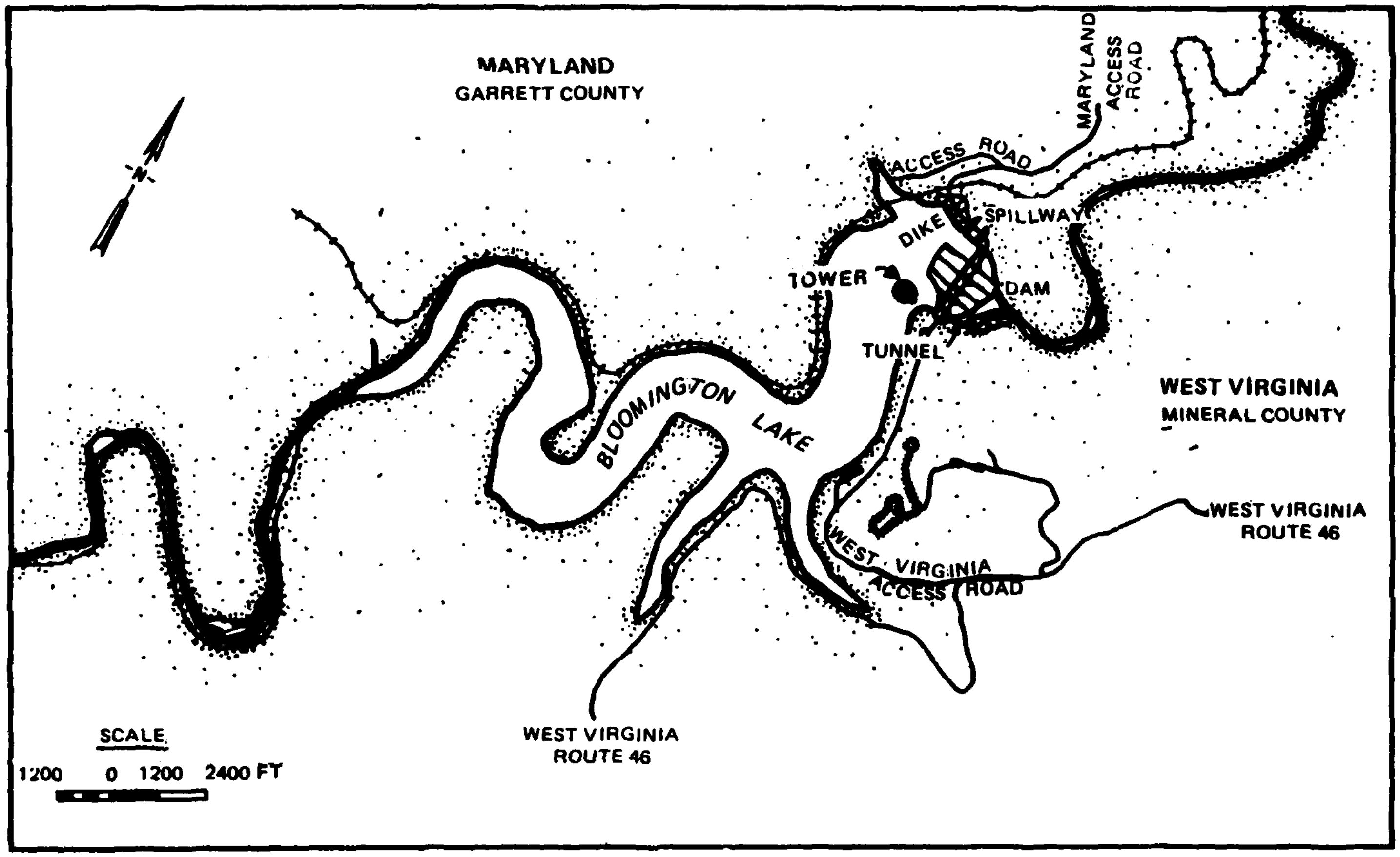


Figure 1. Vicinity map of project location



BLOOMINGTON LAKE

Figure 2. Plan view of project

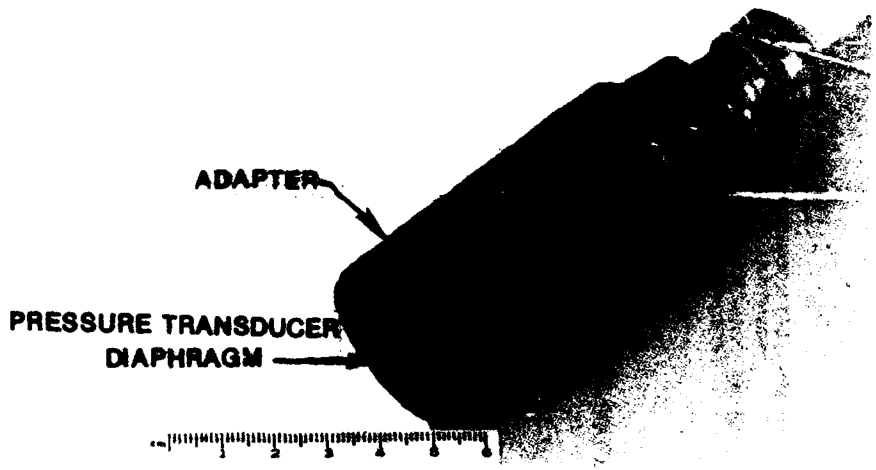


Figure 3. Waterproof pressure transducer adapters

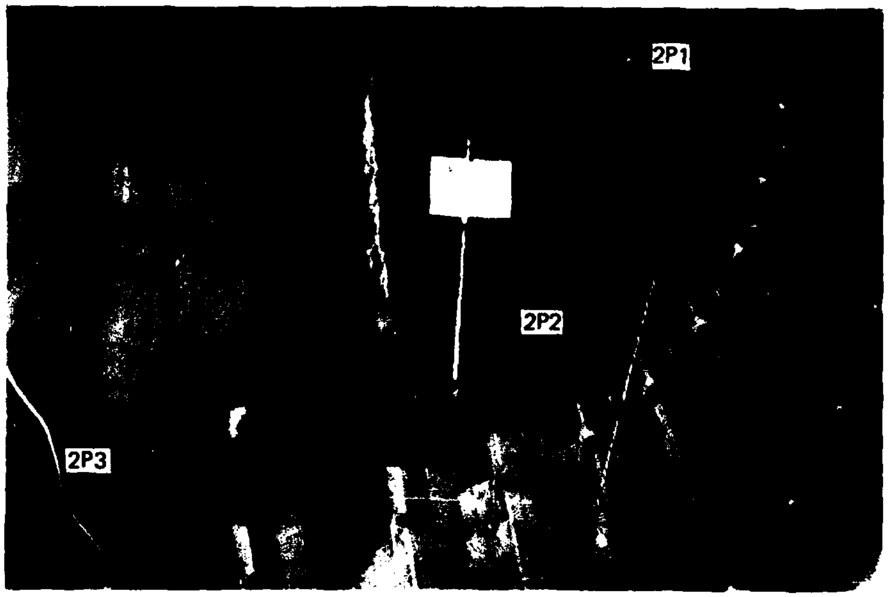


Figure 4. View of locations of transducers 2P3, 2P2, and 2P1 on the transition tube of wet well No. 2

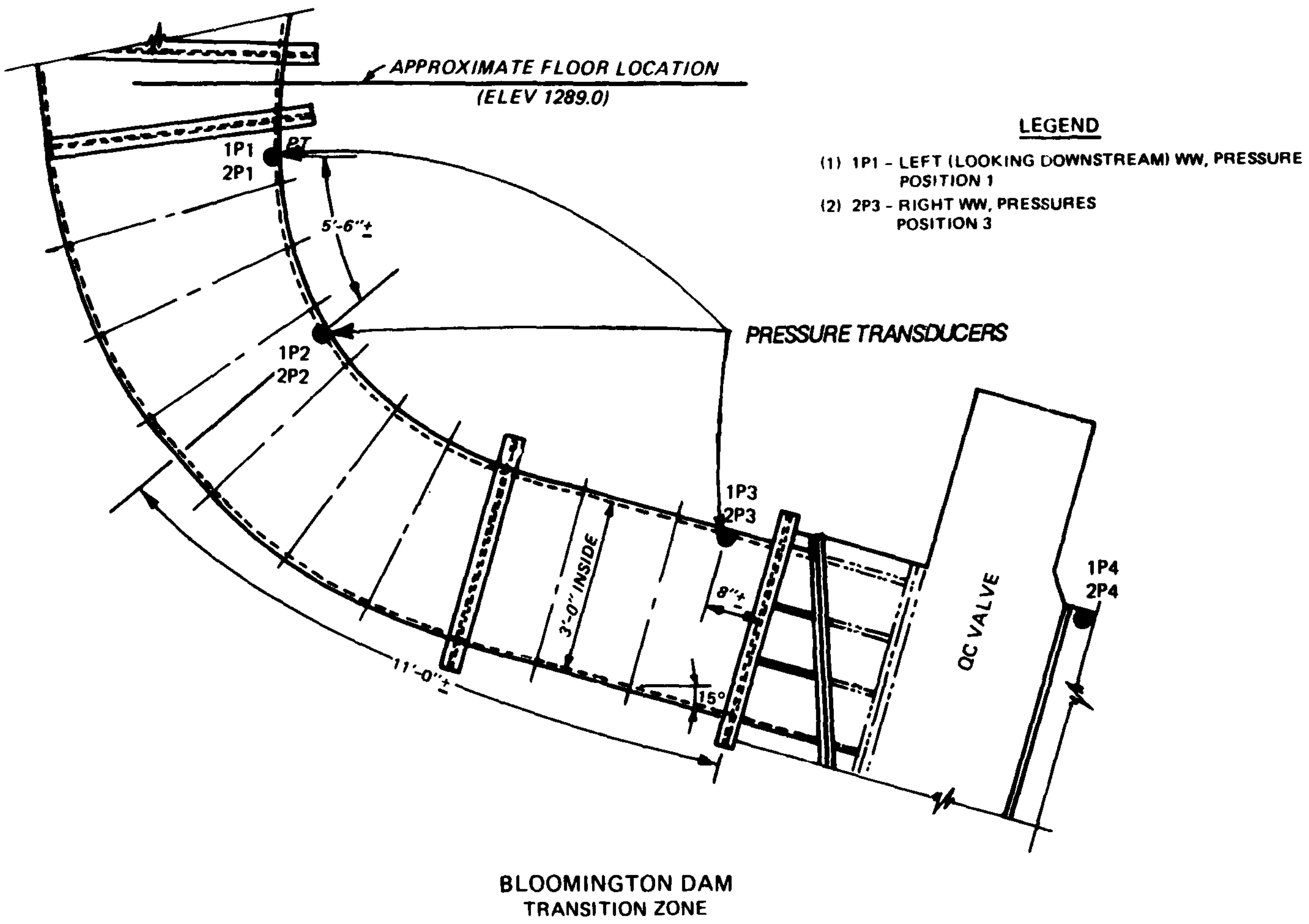


Figure 5. Locations of pressure transducers in wet well transitions

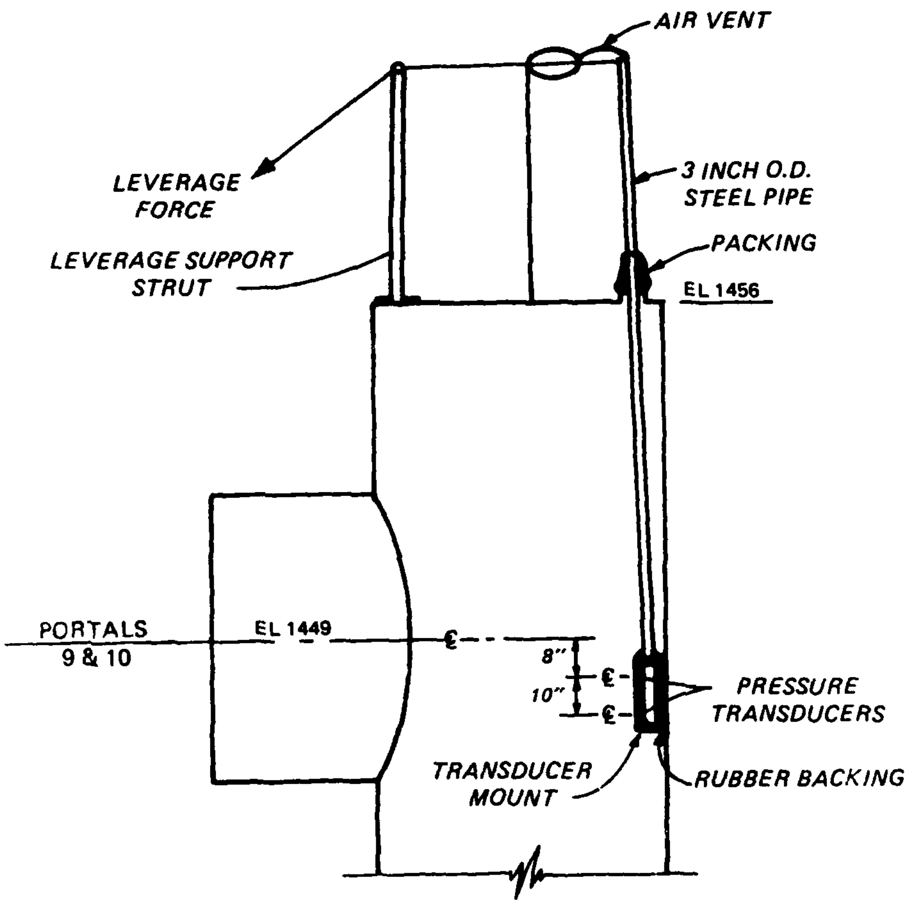


Figure 6. Transducer placement for in situ wet well pressure measurements

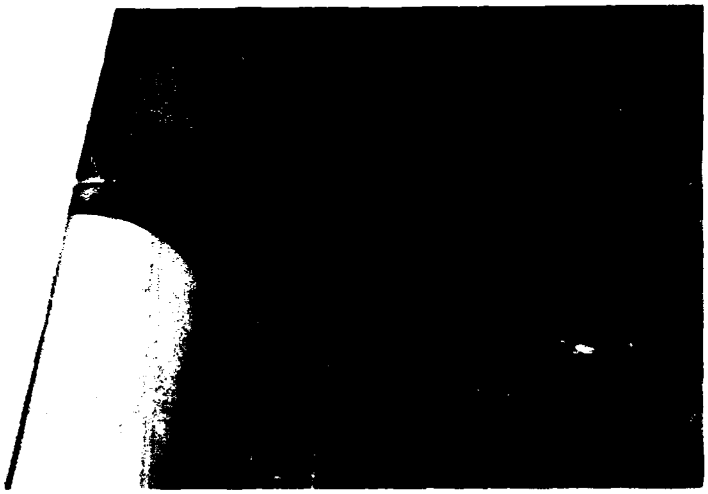


Figure 7. Transducer mount for pressure transducers 1P5 and 1P6 being lowered to wet well No. 1

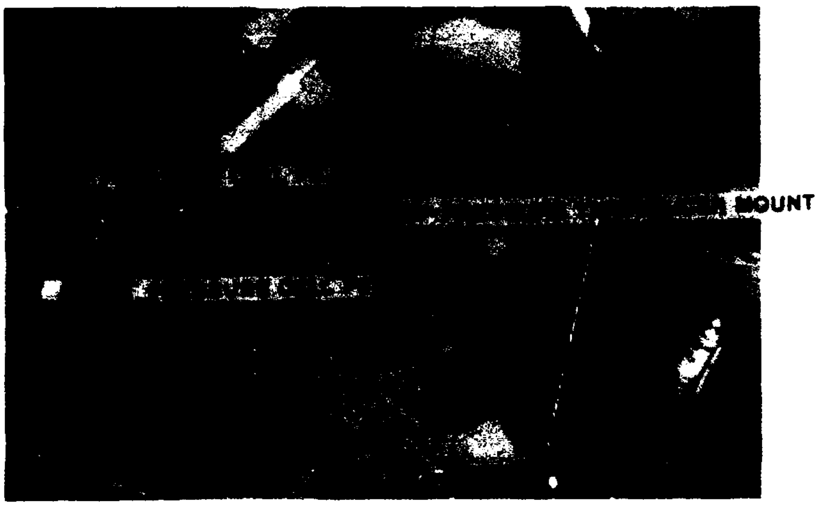


Figure 8. Transducer mount with pressure transducers installed

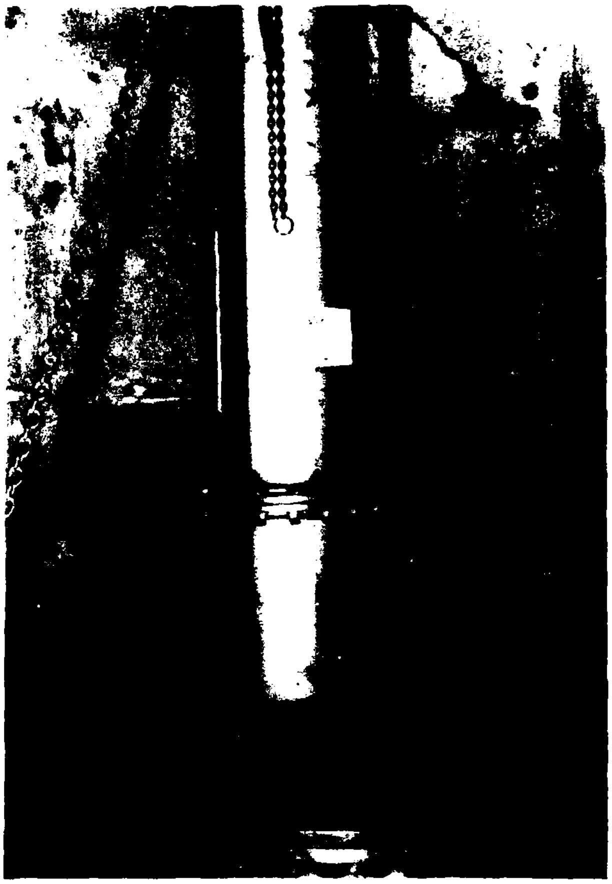


Figure 9. View of mounting system for pressure transducers 1P5 and 1P6 in place in wet well No. 1

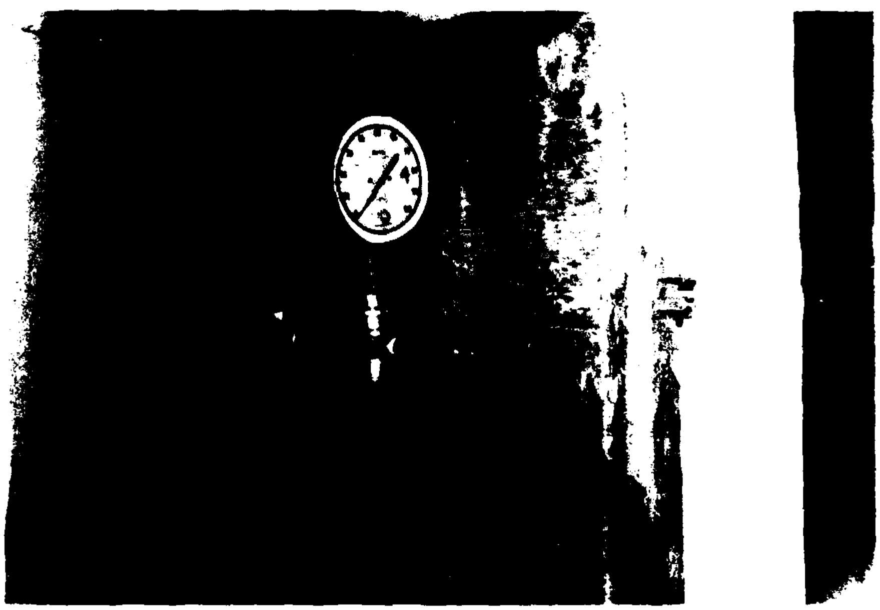


Figure 10. View of pressure tap for hydrostatic pressure measurements at portal 4

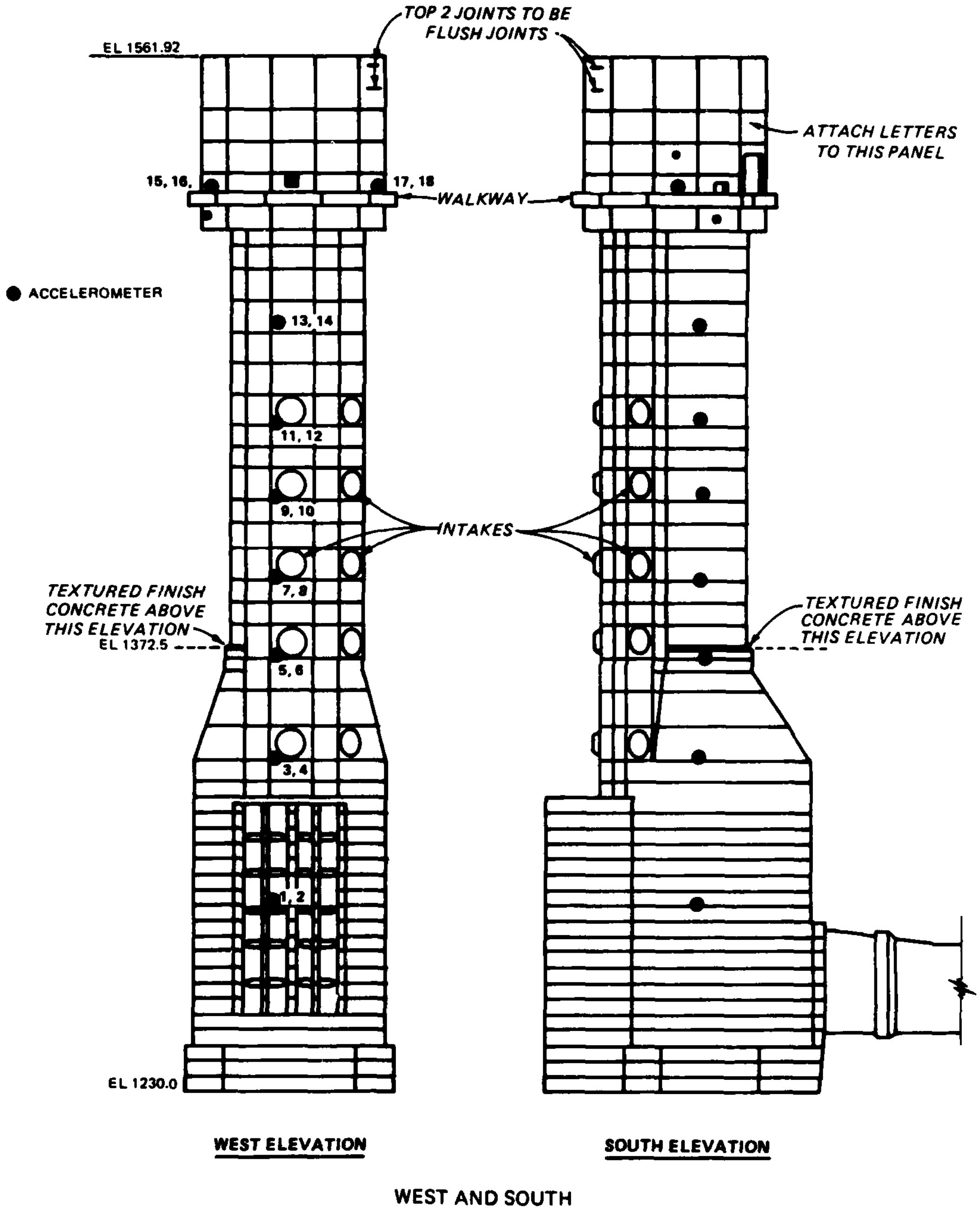
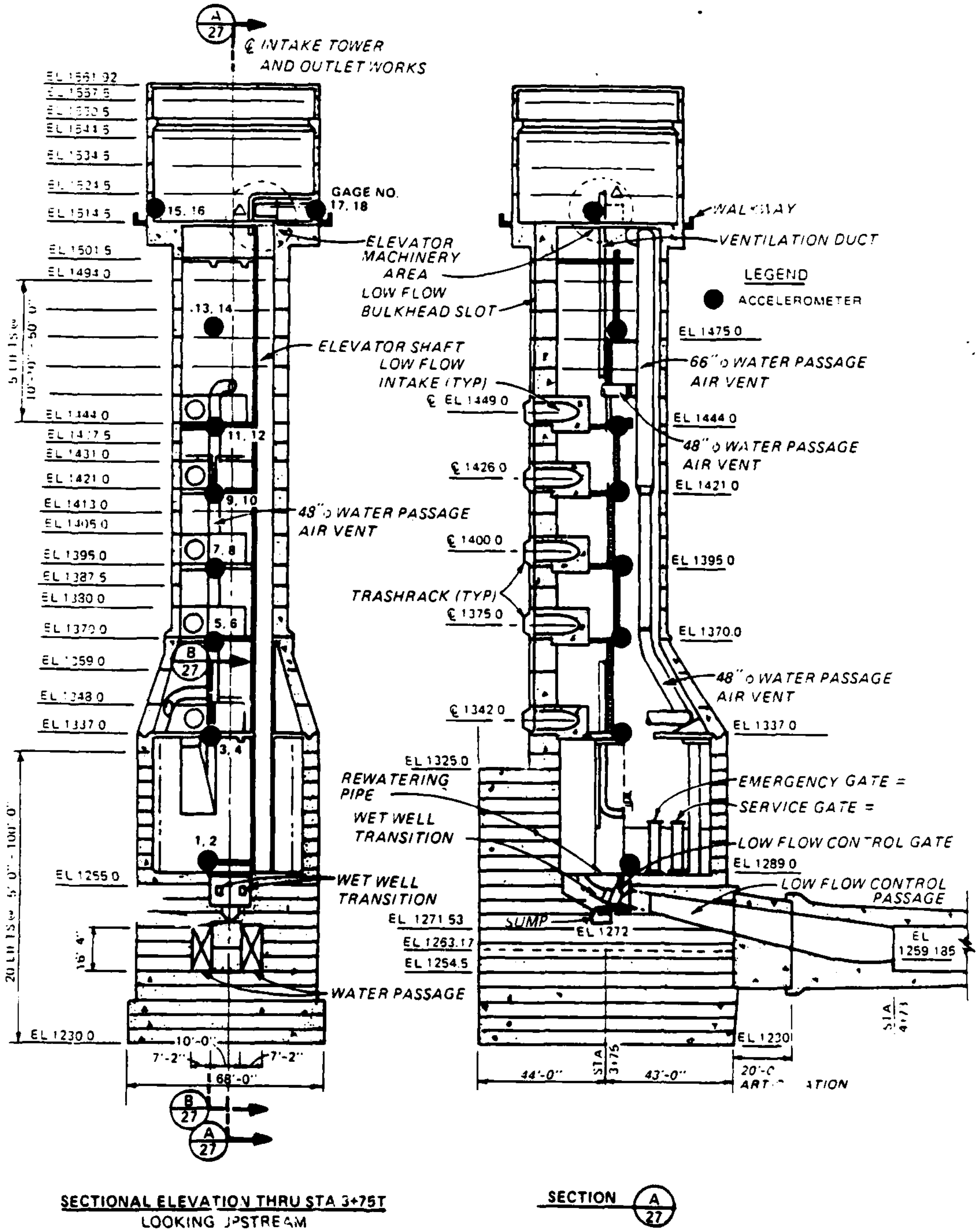


Figure 11. West and south elevations for accelerometer locations



SECTIONAL ELEVATION THRU STA 3+75T
LOOKING UPSTREAM

SECTION A/27

Figure 12. Section views of west and south elevations for accelerometer locations

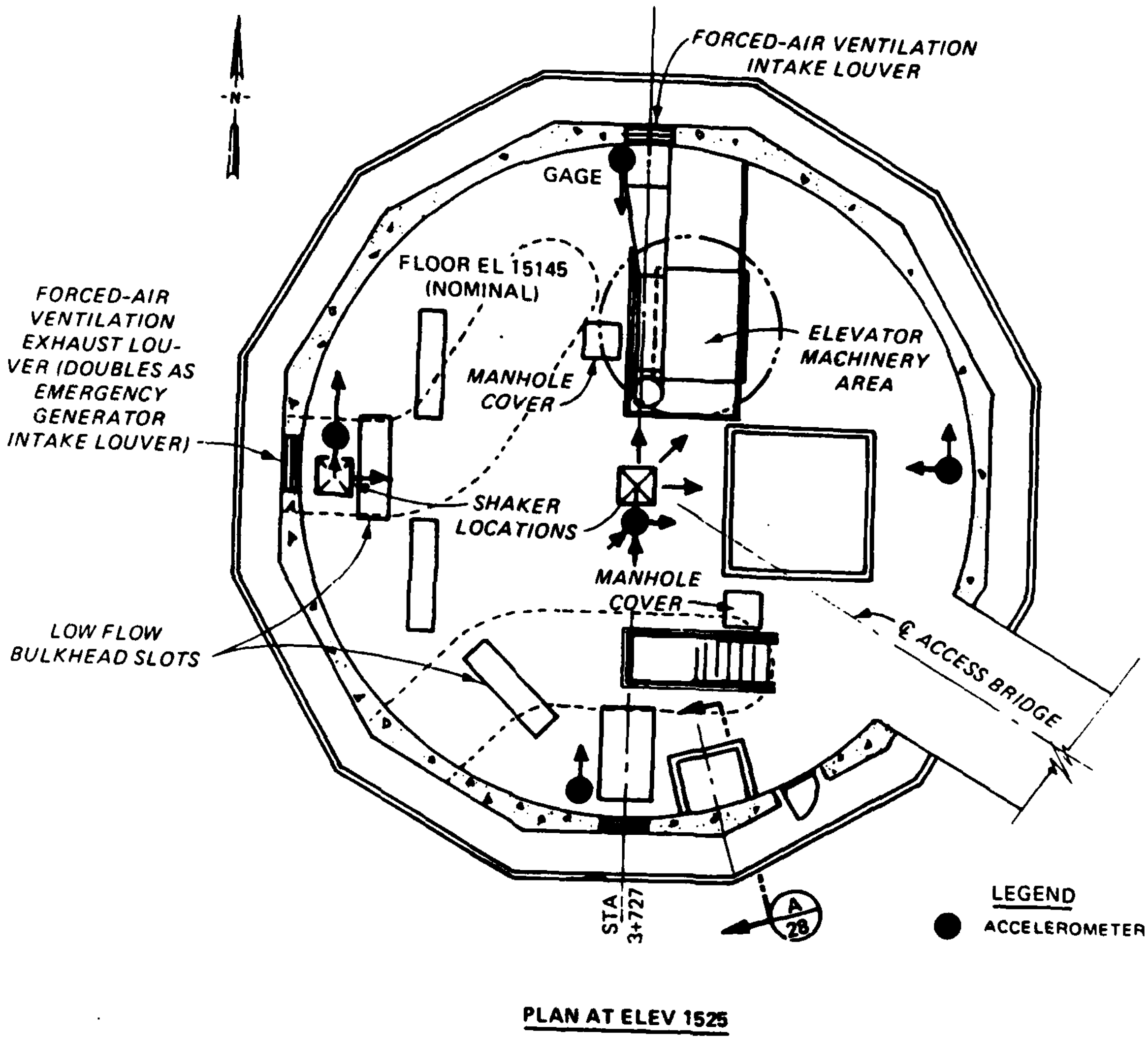
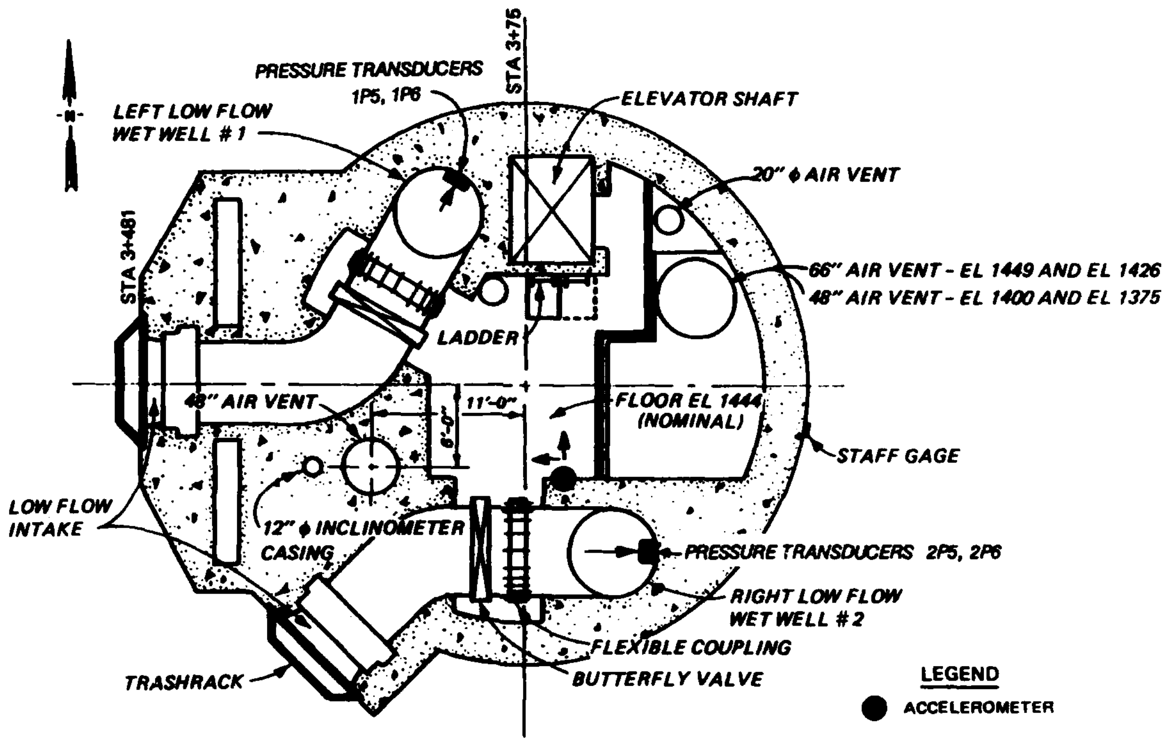


Figure 13. Accelerometer and shaker locations at elevation 1,515.0 ft



PLAN AT ELEV 1449
EL 1426, EL 1400, AND EL 1375 SIMILAR

Figure 14. Typical accelerometer locations below elevation 1,525.0 ft

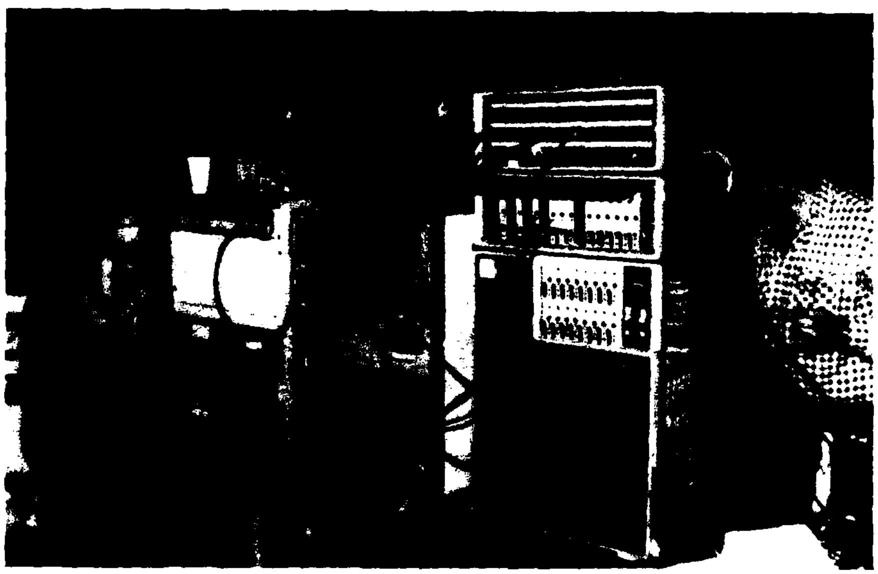


Figure 15. Set up of instrumentation recording and signal conditioning devices

Figure 16. Base plate epoxied to concrete floor at elevation 1,514.5 ft

Figure 17. Zonic ES-302 inertial mass exciter (shaker) mounted on the base plate

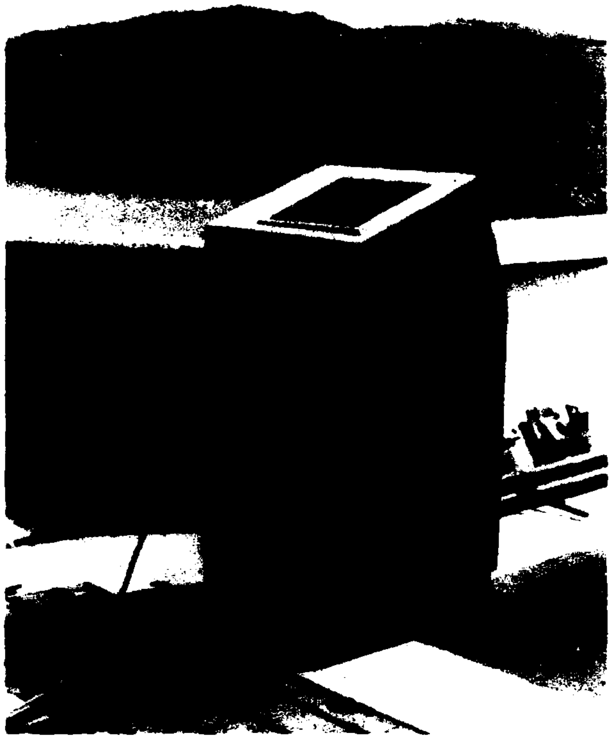


Figure 18. Zonic ES-302 inertial mass exciter hydraulic power supply

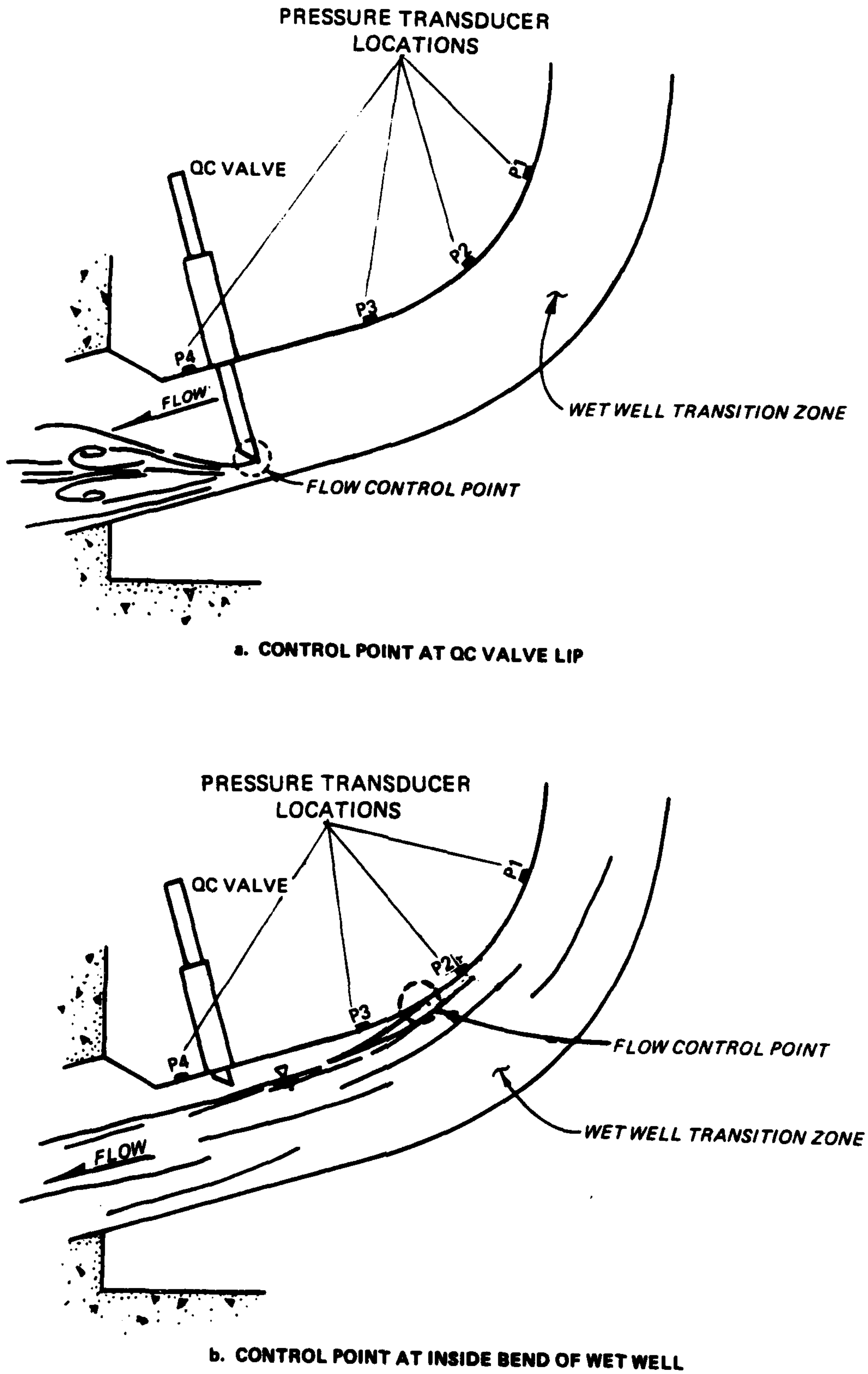


Figure 19. Typical illustration of flow control changing locations

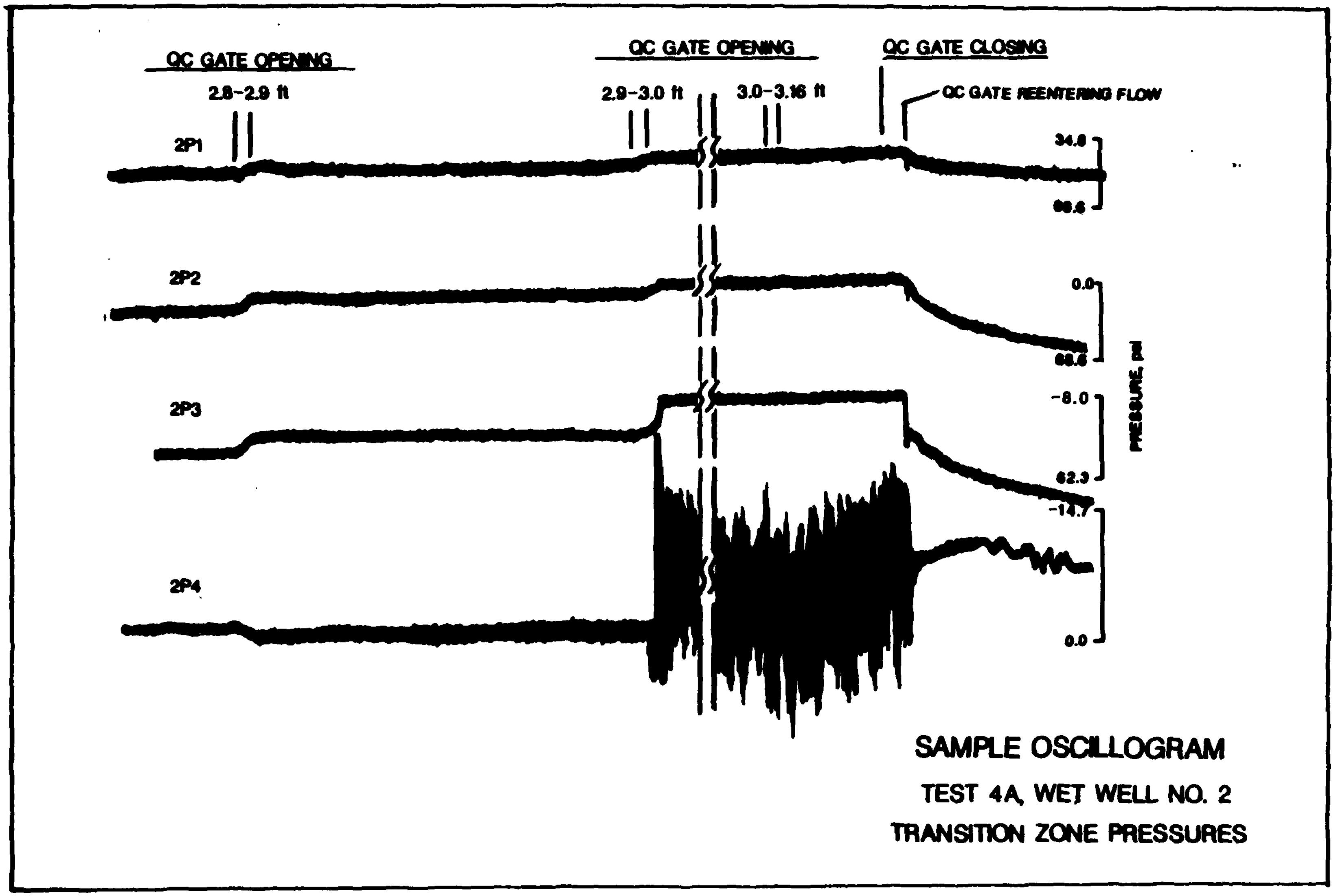


Figure 20. Sample oscillogram illustrating pressure surges occurring upon reentry of QC gate into the flow

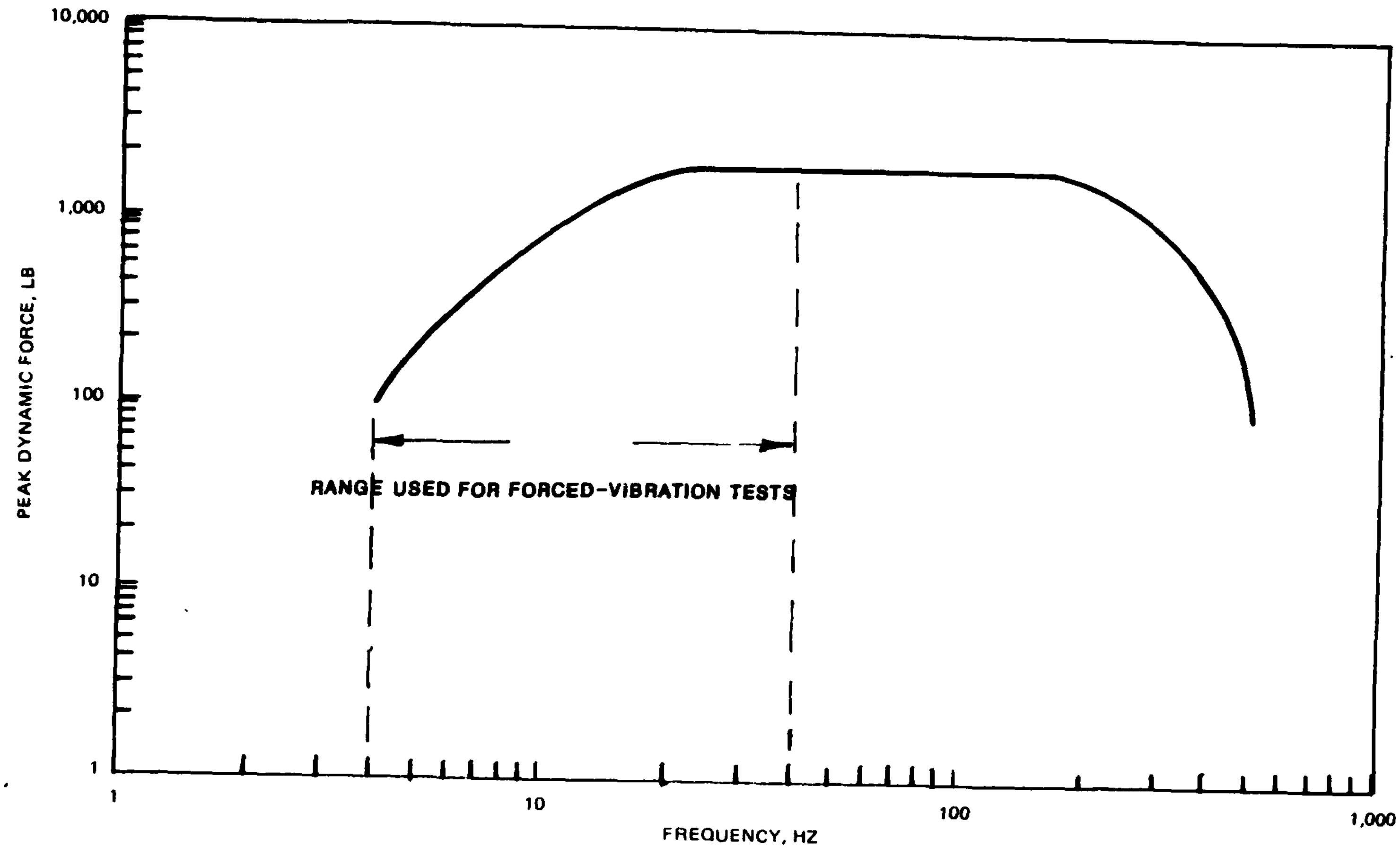


Figure 21. Force spectrum of shaker

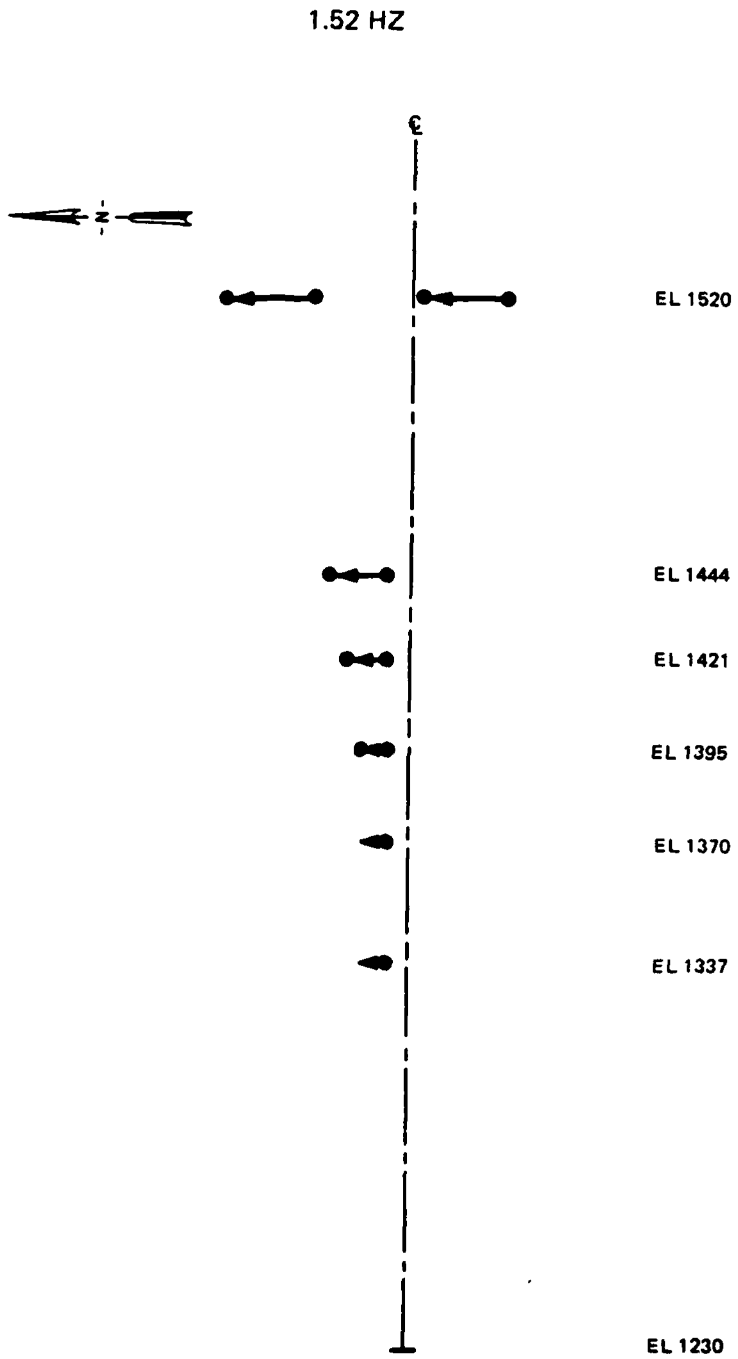


Figure 22. Typical fundamental bending mode of tower

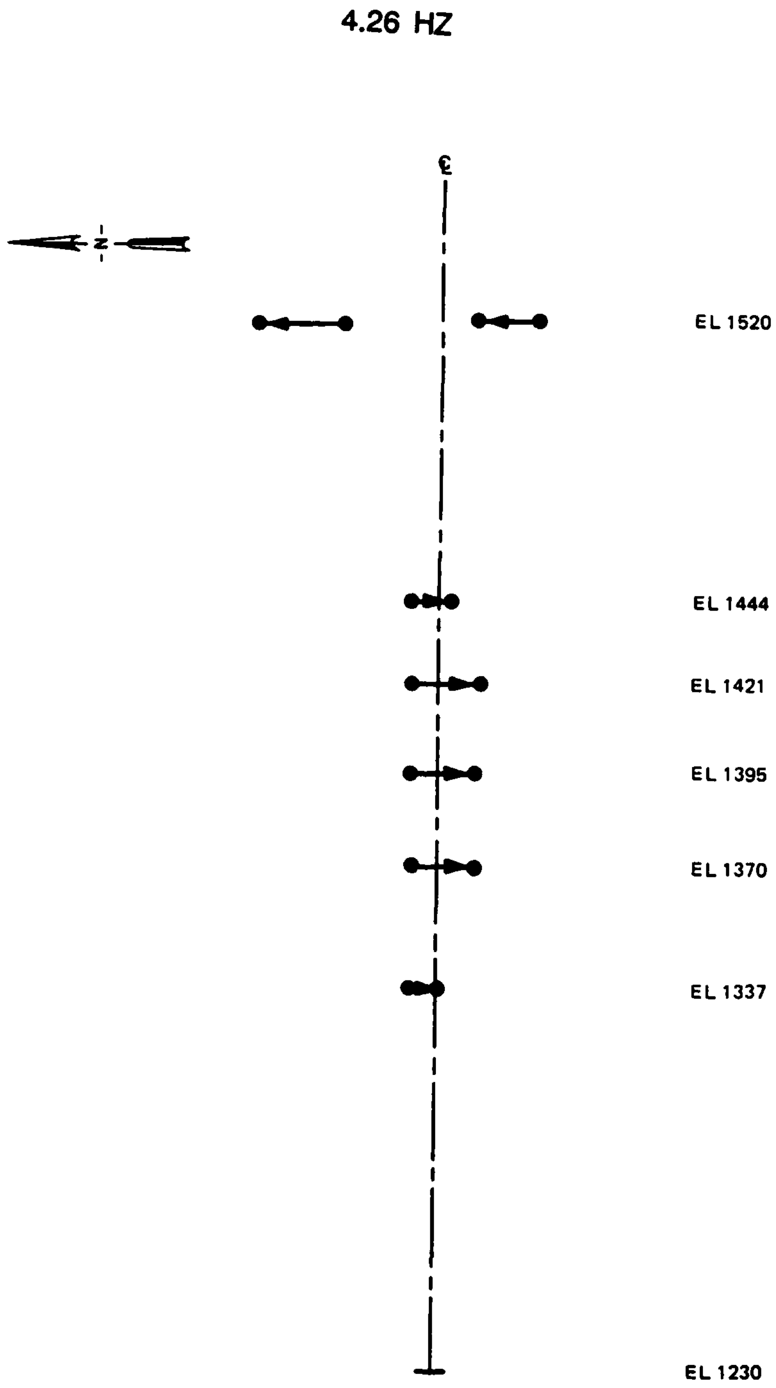


Figure 23. Typical second-order bending mode of tower

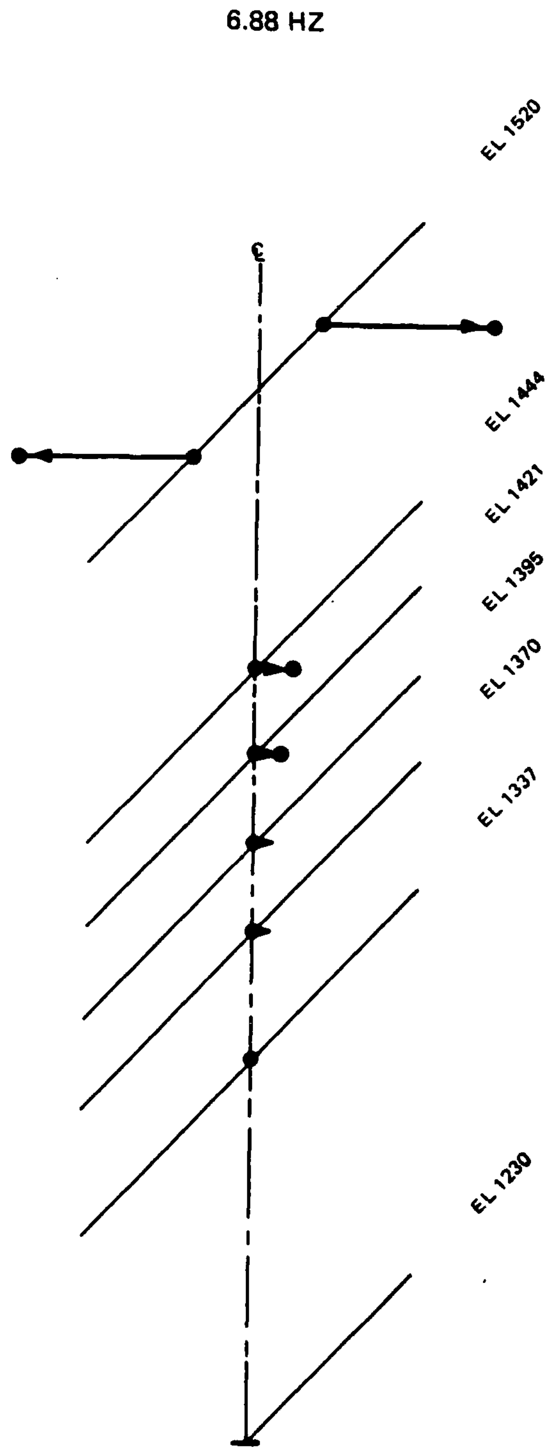


Figure 24. Typical torsional mode of tower

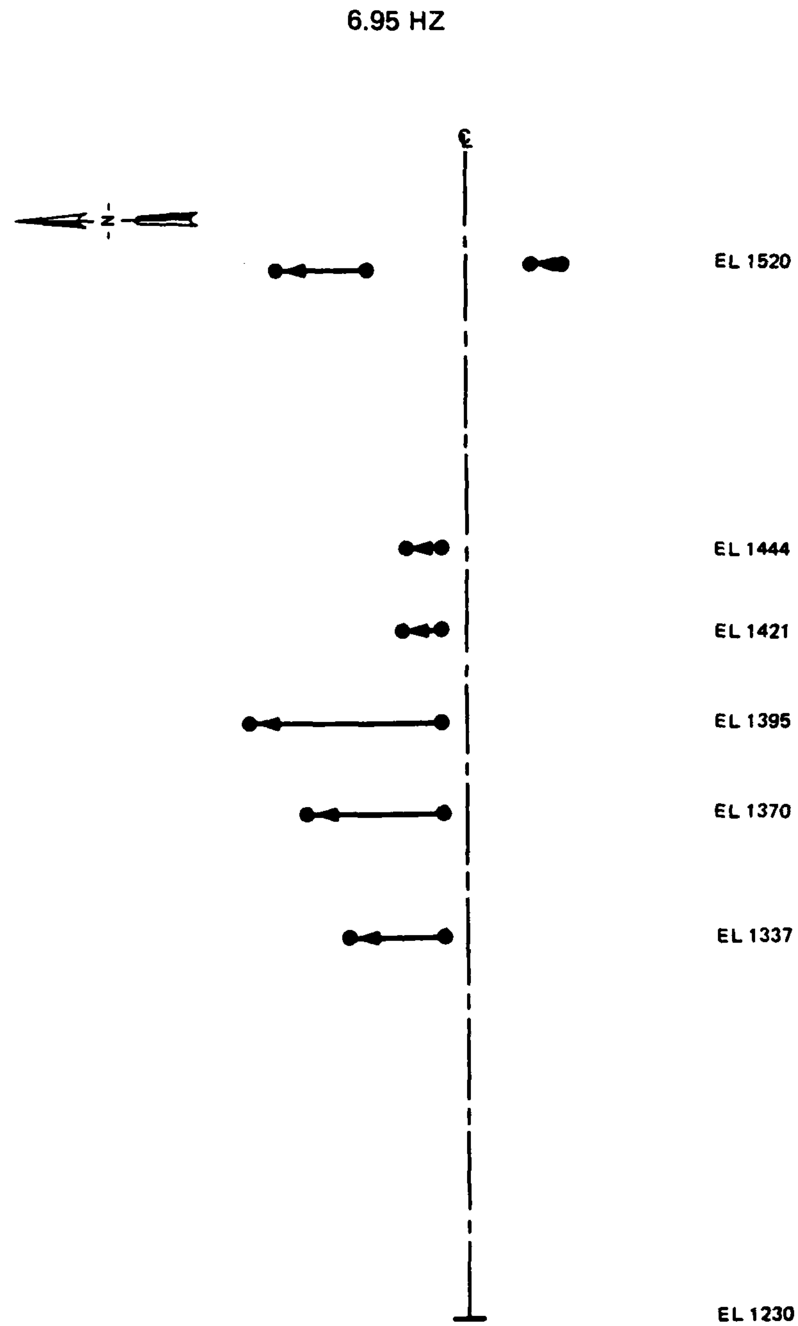


Figure 25. Typical third-order bending mode of tower

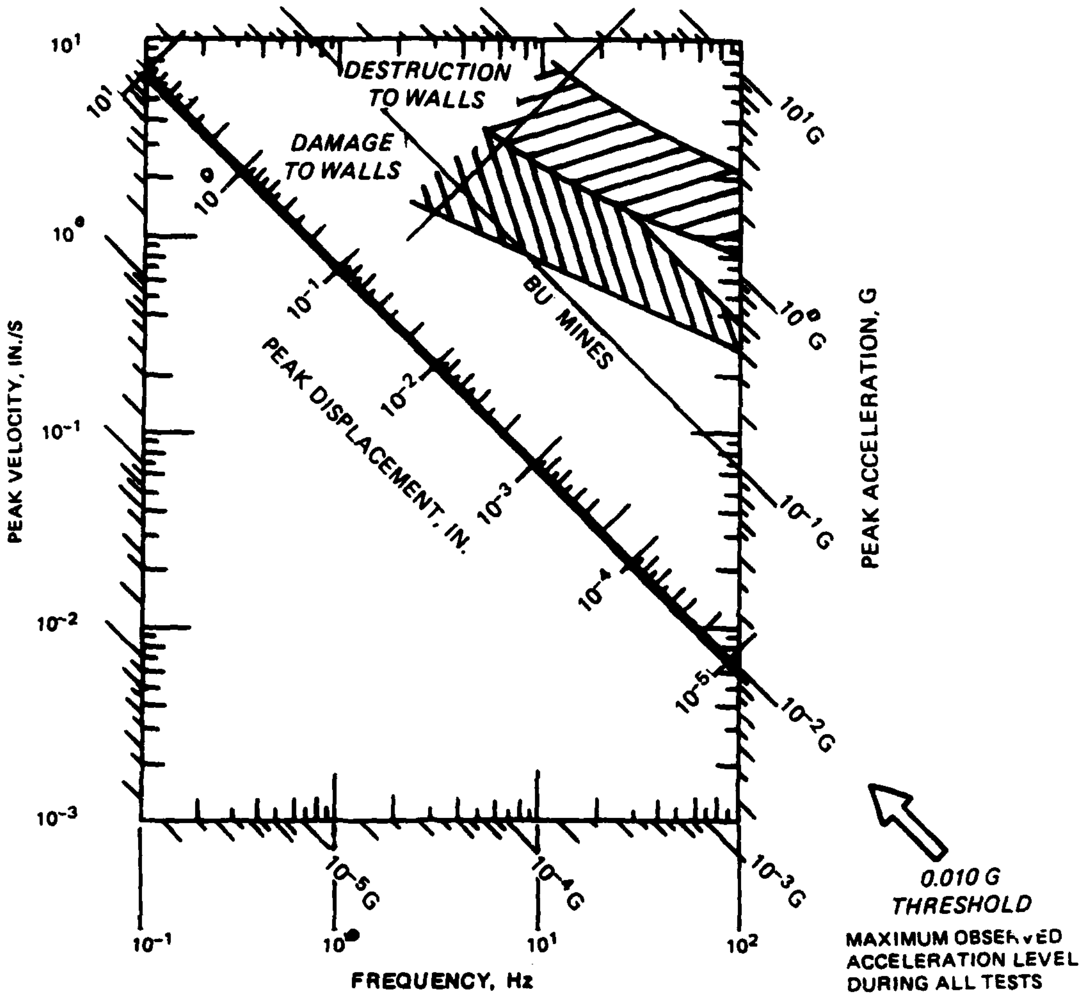


Figure 26. Magnitude of displacement, velocity, and acceleration at observed dominant frequencies